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A FLUID-MECHANICAL MODEL OF THE
THORACO-ABDOMINAL SYSTEM
WITH APPLICATIONS TO BLAST BIOLOGY

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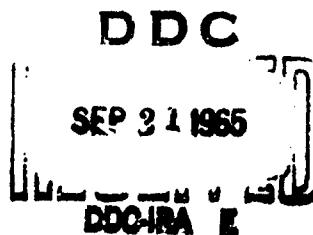
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FOREWORD

This report, describing a fluid-mechanical model of the thoraco-abdominal system derived using theoretical concepts and empirical data, incorporates dimensional analysis, physical and biological scaling, and evaluation of critical parameters to help elucidate mammalian response to sudden changes in environmental pressure.

Though the work shares many limitations common to "state of the art" theoretical explorations, it is nonetheless pertinent to the important area of estimating human responses to blast overpressures from those measured and known to be hazardous in several species of animals of different sizes.

The theoretical, computational and empirical data included in the present study represent part of an ongoing, long-term program aimed at clarifying the biological effects of blast-induced phenomena and assessing the consequences of exposure thereto.

ABSTRACT

A mathematical model was described which was developed to compute some of the fluid-mechanical responses of the thoraco-abdominal system subjected to rapid changes in environmental pressure. The approach -- helpful in understanding many of the primary effects of air blast on animals, but applicable to related problems involving rapid changes in environmental pressure as well -- incorporated an air cavity representing the gaseous volume of the lungs (although it is recognized that gas in the organs of the abdomen may influence the response of the system), two movable pistons and an orifice through which gas might pass in either direction. One of the pistons represented the chest wall and the other that portion of the abdomen which moves with the diaphragm to change the lung volume. Each piston was "assigned" an effective mass and area, a spring constant, and a damping factor. The orifice was taken to "incorporate" the characteristics of the many airways of the respiratory system. Parameters relating the animal to the model were estimated, tested and then adjusted as required by comparing model results with experimental records of thoracic pressures recorded for rabbits exposed to blast waves in shock tubes.

Equations were derived to scale parameters applicable to a given animal to those for similar creatures of arbitrary mass. By dimensional analysis other equations were developed to relate, for a given biological response, the body mass of similar animals to blast wave parameters. Numerical solutions of the model were presented to help explain the mechanisms involved when animals were "loaded" with typical wave forms or with pulses increasing to a maximum in a stepwise manner, a contingency associated with a quite significant increase in mammalian tolerance to over-pressure. Differences in response to "short-" and "long"-duration blast waves were noted. Applications of the scaling concepts were exemplified in several ways making use of the published data in blast biology. In one instance, the blast tolerance of a 70-kg mammal was estimated for sea-level ambient pressure making use of experimental data for dogs and goats obtained at Albuquerque altitude (ambient pressure of 12 psi). That the latter might have significant implications in assessing human response to blast-produced overpressures was discussed along with several other relevant matters.

ACKNOWLEDGMENTS

A FLUID-MECHANICAL MODEL OF THE THORACO-ABDOMINAL SYSTEM WITH APPLICATIONS TO BLAST BIOLOGY

1.0 INTRODUCTION

In the course of studies in blast and shock biology over the past decade, the investigations concerned with the consequences of exposure to blast-induced variations in environmental pressure (primary blast effects) have been given increased attention for at least three reasons. The first is related to the fact that early lethality was known, and further demonstrated, to be among the characteristic responses for all species of mammals exposed to appropriate rises in air pressure produced by actual detonations or by simulated explosions, i.e., by means of shock tubes.[1-10] The second reason is that the magnitude of a hazardous overpressure is significantly lower for "long"-duration, "fast"-rising wave forms that can be produced by nuclear explosives than it is for similar blast waves of shorter duration resulting from detonations of conventional charges of practical sizes.[1,3,6,7-18] The third reason is related to the experimental observation that mammals are extraordinarily sensitive to the rate and character of the pressure rise.[9,10-13,15,18-21] For example, an otherwise lethal blast wave car je tolerated if there is a sufficient delay in the time to maximal pressure or if the pressure is applied in two fast-rising steps separated by an almost unbelievably short interval in time; viz., several tens to hundreds of microseconds depending upon animal size.[8,10,18-23]

Though damage to the lung and the appearance of gas emboli in the coronary and other arteries in blasted mammals no doubt help explain the characteristic early lethality mentioned above,[3-5,7-10,15-19,22-26] the detailed events which are responsible for the origin of the hemorrhages and emboli, until recently, remained obscure as did a satisfactory understanding of the variations in tolerance alluded to previously as connected with changes in the pulse duration and the rate and character of the pressure rise. These matters emphasized the need for paying careful attention to all the physical, biophysical, and biological factors that might help explain the mechanisms of mammalian response to rapid variations in environmental pressure. Generally, previous and recent speculations have centered about (1) the gross implosion process, the violent compression of the body by an air blast wave, (2) the consequent changes in volume of the air-containing organs due to inward movements of the thoracic and abdominal walls and the upward movements of the right and left diaphragms, (3) the associated variations in internal pressure which could be expected to follow application of a specified external pressure

load and, (4) the biological implications of these several pressure relationships. [4, 8, 12, 22, 27-39]

The present study attempts to synthesize these mechanisms in a mathematical model designed to simulate the fluid-mechanical response of the thoraco-abdominal system to sudden changes in environmental pressure. Although the model is simple in concept, it was conceived to represent a complex mammalian organism, making it difficult to determine accurate parameters relating the animal to the model. However, even without numerical evaluation, the model parameters can be subjected to dimensional and similarity analyses to yield important relations between animal mass and blast wave parameters for a given biological response.

The purpose of this report is to relate some of the accomplishments to date. First, the mathematical model (or the lung model for brevity) will be described. Second, a theoretical approach to scaling both the body parameters of mammals and those of the blast wave will be presented. Third, the measures -- direct, devious and arbitrary -- utilized to evaluate the parameters of the lung model will be described and comparisons will be made between pressures measured in the thorax of rabbits during blast and those computed using the model. Fourth, examples of the application of the model in interpreting and predicting selected biological responses will be presented. Fifth, certain of the significant implications of the work will be pointed out and discussed.

2.0 DESCRIPTION OF THE MODEL

2.1 Simplified Functional Concept

An abnormal pressure gradient is established between gas in the lungs and outside air when the local ambient pressure changes so fast that flow in the airways cannot achieve equalization. This is particularily true when a mammal is suddenly engulfed in a blast wave which is characterized by an almost instantaneous rise in pressure. In this case a faster method of pressure equalization takes place simultaneously with flow in the airways; viz., reduction of lung volume by the force of the blast pressures acting on the outside surface of the body to implode the thoracic and abdominal walls. Because of the inertia of the moving parts of the body, overcompensation will occur and the pressures in the lung will, at the completion of the implosive process, momentarily be higher than those outside. Thus, an oscillating system is established which is quickly damped because of frictional losses of energy due to tissue deformation and air motion to and from, and within, the lung.

The processes described above can be stated mathematically and can be evaluated by numerical methods if certain simplifying assumptions are made. The schematic drawing in Fig. 1 illustrates the functional concepts of the model which are discussed in the succeeding paragraphs.

(1) In the model a simple cavity of volume V was used to represent the gaseous volume subject to pressure changes upon movement of the thoraco-abdominal structures, and, for the present, let this volume be that of the lungs and airways which is assumed to be large compared to that of gas in the abdomen in such locations that it could influence the pressure response in the lungs.

(2) Transient variations in volume of the model cavity described above were achieved through the movement of two linear pistons, each characterized by a mass M, an area A, elastic constant K, and damping factor J. One of the pistons represents the chest wall and the other that part of the abdomen which moves with the diaphragm. It is obvious that "effective" values for the above parameters should be used. In the case of the mass and area of the chest wall only those portions which move against the lungs are involved. Even this is an imprecise concept since the chest wall is not flat as is the piston and since some parts of the wall, in response to high transient external pressures, will move a great deal farther than other parts.

The situation for the abdomen is even more complex. The entire abdomen can be considered, for the present, to be a deformable "solid" or a viscious liquid although some gas is known to be present. When this "bag of liquid" is exposed to pressure on its outer surface, the "bag" is deformed and part of its contents move with the diaphragm

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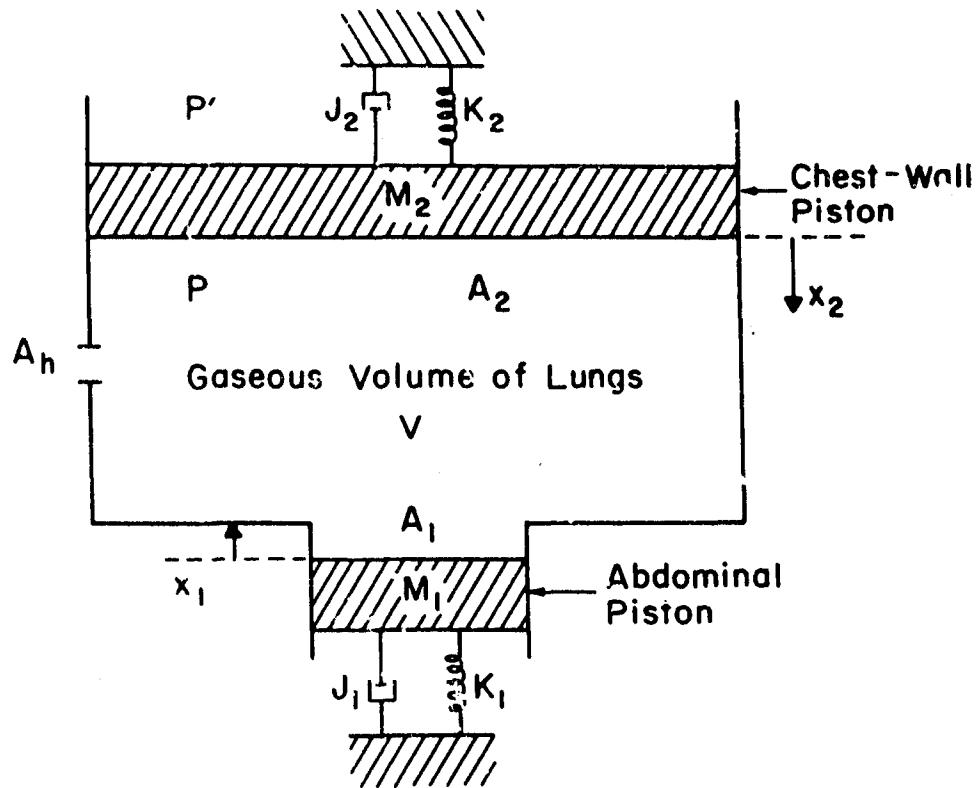
Model Equations

$$M_1 \frac{d^2 x_1}{dt^2} + J_1 \frac{dx_1}{dt} + K_1 x_1 = A_1(P'-P) \qquad (5)$$

$$M_2 \frac{d^2 x_2}{dt^2} + J_2 \frac{dx_2}{dt} + K_2 x_2 = A_2(P'-P) \qquad (6)$$

$$\frac{dP}{dt} = -\gamma \frac{P}{V} \frac{dV}{dt} \pm$$

$$\frac{1.334 \times 10^7 A_h}{V} \sqrt{|P'-P|} \quad \text{cgsu} \qquad (4)$$

$$V = V_0 - x_1 A_1 - x_2 A_2 \qquad (1)$$

Fig. 1   Mathematical model of the thoraco-abdominal system to simulate fluid-mechanical responses to rapid changes in environmental pressure.

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into the space originally occupied by the lungs. As with an open tube of toothpaste under a uniform but transient pressure load over the cylindrical surface, the greatest deformation probably occurs near the outlet (or diaphragm).

(3) In the model, a simple orifice of equivalent area A_h was employed to represent the more complicated airways of the mammal. Though it is likely that the epiglottis and the vocal cords in reality act to impede air flow into and out of the chest under pressure "loading" and "unloading," the area of the orifice was considered to be such that the resulting gas flow would approximate that which actually occurs in the animal.

(4) The pressure and temperature of the gas in the lungs were assumed to be uniform over the entire volume at any given instant of time. This assumption is valid if the velocity of the boundary of the lung is low compared to the propagation velocity of pressure waves within the lung.

(5) It was also assumed that the pressure-volume changes of the pulmonary gas are polytropic and, for lack of definite information, the polytropic exponent was assumed to be 1.2, the average of the exponents for isothermal and adiabatic processes for air.

2.2 Mathematical Statement

If x represents the inward displacement of a piston of area A, (See Figure 1) then the cavity volume V is given by

$$V = V_0 - x_1 A_1 - x_2 A_2 \tag{1}$$

where V_0 is the initial volume and the subscript 1 and 2 refer to the abdominal and chest-wall pistons, respectively.

An expression relating the change in cavity volume to a change in gaseous pressure in the cavity, assuming a polytropic process, is

$$dP_v/dt = -\gamma P/V \, dV/dt \tag{2}$$

where dP_v/dt is the time rate of change of pressure resulting from the rate of volume change dV/dt, P is gaseous pressure in the cavity, and γ is the polytropic exponent, assumed to be 1.2.

Gas in the cavity also experiences a pressure change due to flow through the orifice of area A_h. Since a complete expression of this phenomenon is quite involved, an approximate relation obtained from R. O. Clark[40] was used. The Clark equation, empirically derived from shock tube experiments in which cavities were filled by

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blast-wave flow through orifices, can be written[*]

$$dP_f/dt = \pm (1.334 \times 10^7)(A_h/V) \sqrt{|P' - P|} \quad \text{cgsu} \qquad (3)$$

The quantity dP_f/dt is the time rate of change of pressure in the cavity due to air flow, P' is the outside pressure, and P is the pressure in the cavity. The algebraic sign of the right hand side of the equation is positive if the external pressure P' is greater than the internal pressure P, and negative otherwise. Pressures are expressed in dynes/cm^2, time in seconds, the area A_h in cm^2, and the volume V in cm^3.

The net change in the pressure of the gas in the cavity was assumed to be the sum of Eqs. (2) and (3).

$$dP/dt = dP_v/dt + dP_f/dt$$
$$= -\gamma P/V \; dV/dt \pm (1.334 \times 10^7)(A_h/V) \sqrt{|P' - P|} \quad \text{cgsu} \quad (4)$$

The analysis presented above described cavity volume as a function of piston position, Eq. (1), and gaseous pressures in the cavity as a function of volume and air flow, Eq. (4). It now remains to investigate piston motion as a function of the pressure difference, $P' - P$.

The piston experiences a driving force because of the difference in internal and external pressure $(P' - P)$ acting on the piston area A. Opposing the driving force are the forces due to inertia $M \; d^2x/dt^2$, friction $J \; dx/dt$, and elasticity Kx, where M is the piston mass, x is the piston displacement, J is the frictional force per unit velocity, and K is the elastic force per unit displacement. Stated in equation form, the following is obtained:

$$M_1 \; d^2x_1/dt^2 + J_1 \; dx_1/dt + K_1 x_1 = A_1 (P' - P) \qquad (5)$$

$$M_2 \; d^2x_2/dt^2 + J_2 \; dx_2/dt + K_2 x_2 = A_2 (P' - P) \qquad (6)$$

The subscripts 1 and 2 refer to the pistons representing the abdominal system and the chest wall, respectively. The quantities M, J, K, and A, are assumed to be constant for a given mammal. The external pressure P' is expressed as a function of time, and the internal pressure P is determined by air flow and the instantaneous lung volume.

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[*] A more accurate method for computing the pressure change due to air flow is being developed and will be described in a subsequent report. The method reported here, however, is satisfactory for the usual blast situation.

2.3 Numerical Method of Solution

For convenience of solution, Eqs. (5) and (6) were written in terms of velocity v instead of displacement x by the following transformations:

$$d^2 x / dt^2 = dv/dt$$

$$dx/dt = v$$

$$x = \int_0^t v \, dt$$

A digital computer was used to solve the model Eqs. (1), (4), (5), and (6) simultaneously for small time steps* employing the following approximations:

    (1)   First derivatives were replaced by their finite-difference ratios.

    (2)   Functions were approximated by their average values over the time interval assuming that the responses were linear.

    (3)   Integrals were approximated by their cumulative sums, summed over the previous integration steps.

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* The time steps used varied from 1.0 to 12 μ sec depending on the response time of the animal simulated.

3.0   DIMENSIONAL ANALYSIS AND SCALING

3.1 Model Equations in Dimensionless Form

The model equations developed in Section 2.2. are summarized below.

$$d^2 x_1/dt^2 + (J_1/M_1)\ dx_1/dt + (K_1/M_1)\ x_1 = (A_1/M_1)\ (P' - P) \tag{7}$$

$$d^2 x_2/dt^2 + (J_2/M_2)\ dx_2/dt + (K_2/M_2)\ x_2 = (A_2/M_2)\ (P' - P) \tag{8}$$

$$dP/dt = -(\gamma P/V)\ dV/dt \pm (1.334 \times 10^7)\ (A_h/V)\ \sqrt{|P' - P|} \quad \text{cgsu} \tag{4}$$

$$V = V_0 - x_1 A_1 - x_2 A_2 \tag{1}$$

~~ introducing the ambient air pressure, P_0, and the total body mass of the animal, m, various systems of dimensionless quantities were developed for these model equations. The most meaningful one is presented below:

$$d^2 \underline{X}_1/d\underline{T}^2 + \underline{J}_1\ d\underline{X}_1/d\underline{T} + \underline{K}_1 \underline{X}_1 = \underline{A}_1\ (\underline{P}' - \underline{P}) \tag{9}$$

$$d^2 \underline{X}_2/d\underline{T}^2 + \underline{J}_2\ d\underline{X}_2/d\underline{T} + \underline{K}_2 \underline{X}_2 = \underline{A}_2\ (\underline{P}' - \underline{P}) \tag{10}$$

$$d\underline{P}/d\underline{T} = -(\gamma\underline{P}/\underline{V})\ d\underline{V}/d\underline{T} \pm (\underline{A}_h/\underline{V})\ \sqrt{|\underline{P}' - \underline{P}|} \tag{11}$$

$$\underline{V} = 1 - \underline{A}_1 \underline{X}_1 - \underline{A}_2 \underline{X}_2 \tag{12}$$

The definitions of the underlined dimensionless quantities (numerics) are:

Cavity Pressure	$\underline{P} = P/P_0$	(13)
External Pressure	$\underline{P}' = P'/P_0$	(14)
Cavity Volume	$\underline{V} = V/V_0$	(15)
Time	$\underline{T} = t\ \sqrt{P_0 V_0^{1/3}/m}$	(16)
Displacement of abdominal piston	$\underline{X}_1 = x_1/V_0^{1/3}$	(17)
Displacement of chest-wall piston	$\underline{X}_2 = x_2/V_0^{1/3}$	(18)
Damping factor for abdominal piston	$\underline{J}_1 = (J_1/M_1)\ \sqrt{m/(P_0 V_0^{1/3})}$	(19)
Damping factor for chest-wall piston	$\underline{J}_2 = (J_2/M_2)\ \sqrt{m/(P_0 V_0^{1/3})}$	(20)
Spring constant for abdominal piston	$\underline{K}_1 = K_1 m/(M_1 P_0 V_0^{1/3})$	(21)

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Spring constant for chest-wall
piston

$$\underline{K}_2 = K_2 m/(M_2 P_o V_o^{1/3}) \qquad (22)$$

Area of abdominal piston

$$\underline{A}_1 = A_1 m/(V_o^{2/3} M_1) \qquad (23)$$

Area of chest-wall piston

$$\underline{A}_2 = A_2 m/(V_o^{2/3} M_2) \qquad (24)$$

Area of orifice

$$\underline{A}_h = 1.334 \times 10^? A_h m^{1/2}/(P_o V_o^{7/6})$$
$$\text{cgsu} \qquad (25)$$

The dimensional quantities are

P,	pressure in the cavity, or internal pressure,
P',	external pressure, a function of time,
P_o	ambient pressure,
A_1,	area of abdominal piston,
A_2,	area of chest-wall piston,
x_1,	displacement of abdominal piston,
x_2,	displacement of chest-wall piston,
V,	volume of the cavity,
V_o,	initial volume of the cavity,
t,	time,
m,	total body mass of the animal,
M_1,	mass of the abdominal piston,
M_2,	mass of the chest-wall piston,
A_h,	area of the orifice representing the respiratory airways of the animal,
J_1,	damping factor of the abdominal piston, force per unit velocity,
J_2,	damping factor of the chest-wall piston, force per unit velocity,
K_1,	spring constant of the abdominal piston, force per unit displacement
K_2,	spring constant of the chest-wall piston, force per unit displacement

It should be noted that the number 1.334×10^7 in Eq. (25) has the units $\sqrt{\text{dynes}/\text{sec}}$ and hence caution must be used with regard to the units of the other quantities in the equation to insure that a computed $\underline{A}_h$ will be truly dimensionless.

It will be necessary to develop concepts of similarity among animals before the significance of the dimensional analysis presented above can be fully appreciated.

3.2 Animal Similarity

It was assumed for all animals of a particular group or species that the shape is the same and that the spatial distributions

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of tissue density, stretch (Young's) modulus, shear modulus, bulk
modulus, and Poisson's ratio are equivalent (equal at corresponding
points). Because equivalence implies similarity, a single character-
istic length L, tissue density ρ_0, stretch modulus Y_0, shear modulus
S_0, bulk modulus B_0, and Poisson's ratio σ_0 are sufficient to specify
the animal for purposes of dimensional analysis.

It then follows that

$$A_1 / V_0^{2/3} \quad = \quad C_1 \tag{26}$$

$$A_2 / V_0^{2/3} \quad = \quad C_2 \tag{27}$$

$$M_1 / m \quad = \quad C_3 \tag{28}$$

$$M_2 / m \quad = \quad C_4 \tag{29}$$

$$V_0 / m \quad = \quad C_5 \tag{30}$$

$$A_h / V_0^{2/3} \quad = \quad C_6 \tag{31}$$

$$L / m^{1/3} \quad = \quad C_7 \tag{32}$$

$$K_1 / (Y_0 L) \quad = \quad f_1 (S_0/Y_0, \; B_0/Y_0, \; \sigma_0) \tag{33}$$

$$K_2 / (Y_0 L) \quad = \quad f_2 (S_0/Y_0, \; B_0/Y_0, \; \sigma_0) \tag{34}$$

where the f's are unspecified functions and the C's are constants.
(Note that the spring constants, K_1 and K_2, are inertia-free
quantities and would therefore be independent of tissue density.)
Remembering that Y_0, S_0, B_0, and σ_0 are assumed to be constant
for all animals in the group, Eqs. (32), (33), and (34) can be
combined to give

$$K_1 / m^{1/3} \quad = \quad C_8 \tag{35}$$

$$K_2 / m^{1/3} \quad = \quad C_9 \tag{36}$$

The remaining animal parameters to be considered are
the damping factors for the abdominal and chest-wall pistons.
Damping is introduced in the model equations to account for various
irreversible processes due to tissue deformation and air motion.

The experimental information on damping available in
the physiological literature relevant to the pressure responses of
the chest and airways* is concerned with processes which take
place slowly compared to those resulting from exposure to air
blast. Such processes are slow enough to allow flow of air to and
from the lungs, in fact, this is an important mechanism involved
in the cited investigations. On the other hand, the blast-induced
processes appear to be so fast that no significant flow can take place in the

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* See, for example, Refs. 41, 42, and 43.

airways although some movement of gas would be expected in the tortuous passageways within the lung itself. Such flow would be more heavily damped than that in the entire respiratory tract. Thus, it is evident that the damping processes involved in the blast situation are complex and cannot be rel 'ed directly to those involved in conventional physiological studies.

Without a precise understanding of the damping processes, it seems reasonable to assume that the "effective" damping, or damping ratio, of all species of animals is the same,; i. e., for all animals, the damping factor divided by the critical damping factor (which would just prohibit oscillations) is the same. Expressed algebraically,

$$\alpha = J/J_c = J/(2\sqrt{K'M}) = \text{constant} \tag{37}$$

where α is the damping ratio, J is the damping factor, J_c is the critical damping factor, K' is the <u>effective</u> spring constant, and M is the mass being moved.

The coefficient K' is the sum of the effects of (1) the tissue spring assumed to be linear and described in the model equations as K_1 and K_2 and (2) the non-linear air spring resulting from the fact that the animal's response to blast is so rapid that the air initially in the lungs is essentially trapped. If it is assumed that air flow to and from the lungs is not significant,[*] the pressure-volume relation can be written as

$$PV^\gamma = P_0 V_0^\gamma \tag{38}$$

where P is the pressure in the lung when its volume is V, γ is the polytropic exponent, and P_0 is the pressure in the lung when its volume is V_0. Differentiating Eq. (38),

$$dP/dV = -\gamma P/V \tag{39}$$

The pressure differential dP is by definition equal to $-dF/A$ and the volume differential is defined by the model as $-A\,dx$, where dF is the differential force on the piston of area A and dx is the incremental piston displacement. Thus Eq. (39) can be written in terms of the non-linear spring "constant" as

$$dF/dx = -\gamma A^2 P/V \tag{40}$$

The variable volume V can be eliminated from Eq. (40) by introducing Eq. (38).

$$dF/dx = -(\gamma A^2 P/V_0)\,(P/P_0)^{1/\gamma} \tag{41}$$

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[*] Experimental evidence pertaining to air flow during the blast experience can be found in Refs. 4 and 44.

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The effective spring coefficient can now be expressed as

$$K' = K - dF/dx$$
$$= K + (\gamma A^2 P/V_0)(P/P_0)^{1/\gamma} \tag{42}$$

so that Eqs. (42) and (37) can be combined to give

$$J = 2\alpha M^{1/2}[K + (\gamma A^2 P/V_0)(P/P_0)^{1/\gamma}]^{1/2} \tag{43}$$

Making use of the scaling relations in Eqs. (26) - (36), Eq. (43) can be written for the two pistons

$$J_1/m^{2/3} = 2\alpha [C_3 C_8 + \gamma C_1^2 C_3 C_5^{1/3} P (P/P_0)^{1/\gamma}]^{1/2} \tag{44}$$

$$J_2/m^{2/3} = 2\alpha [C_4 C_9 + \gamma C_2^2 C_4 C_6^{1/3} P (P/P_0)^{1/\gamma}]^{1/2} \tag{45}$$

In the absence of direct evidence it was assumed that the damping ratio has a constant value α_0 for all animal species when both P and P_0 have a value of, say, 1.013×10^6 dynes/cm^2 (14.7 psi). Eqs. (44) and (45) can then be written

$$J_1/m^{2/3} = 2\alpha_0 [C_3 C_8 + \gamma C_1^2 C_3 C_5^{1/3}(1.013 \times 10^6)]^{1/2} \quad \text{cgsu} \tag{46}$$

$$J_2/m^{2/3} = 2\alpha_0 [C_4 C_9 + \gamma C_2^2 C_4 C_6^{1/3}(1.013 \times 10^6)]^{1/2} \quad \text{cgsu} \tag{47}$$

or

$$J_1/m^{2/3} = C_{10} \tag{48}$$

$$J_2/m^{2/3} = C_{11} \tag{49}$$

It is of interest to note for a given animal (J and m both constant) the change in the damping ratio α caused by changes in P and P_0; an increase in P_0 results in an increase in the damping ratio but an increase in P lowers it. See Eq. (43). During oscillation the average internal pressure is about the same as the external; thus, for exposures at a given ambient pressure, the thoraco-abdominal system would vibrate more freely in response to a blast wave of "long" duration than it would to one of "short" duration -- the durations being "long" or "short" relative to the period of oscillation.

Similarly, "long" - duration blast waves of small magnitude would produce oscillations with greater damping than would corresponding waves of larger magnitude.

3.3 Environmental-Pressure Scaling for Similar Animals of Different Masses

The model-equation numerics defined in Eqs. (13) - (25) can be simplified by using the similarity relations in Eqs. (26) - (36), (48), and (49) to eliminate M_1, M_2, K_1, K_2, J_1, J_2, A_1, A_2, A_h, and V_0

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as scaling parameters. For completeness, Eqs. (13) and (14)
are repeated.

$$\underline{P} = (P/P_0) \tag{13}$$

$$\underline{P}' = (P'/P_0) \tag{14}$$

$$\underline{V} = (V/m)\,(C_6^{-1}) \tag{44}$$

$$\underline{T} = (tP_0^{1/2}/m^{1/3})\,(C_6^{1/6}) \tag{45}$$

$$\underline{X}_1 = (x_1/m^{1/3})\,(C_6^{-1/3}) \tag{46}$$

$$\underline{X}_2 = (x_2/m^{1/3})\,(C_6^{-1/3}) \tag{47}$$

$$\underline{J}_1 = (1/P_0^{1/2})\,(C_3^{-1}\,C_6^{-1/3}\,C_{10}) \tag{48}$$

$$\underline{J}_2 = (1/P_0^{1/2})\,(C_4^{-1}\,C_6^{-1/3}\,C_{11}) \tag{49}$$

$$\underline{K}_1 = (1/P_0)\,(C_3^{-1}\,C_6^{-1/3}\,C_8) \tag{50}$$

$$\underline{K}_2 = (1/P_0)\,(C_4^{-1}\,C_6^{-1/3}\,C_9) \tag{51}$$

$$\underline{A}_1 = (C_1\,C_3^{-1}) \tag{52}$$

$$A_2 = (C_2\,C_3^{-1}) \tag{53}$$

$$A_h = (1/P_0)\,(1.334 \times 10^7\,C_6\,C_6^{-1/2})\quad \text{cgsu} \tag{54}$$

Note that the animal-parameter numerics defined by Eqs. (52)
and (53) have constant values (independent of animal mass and ambient
pressure); the remaining animal numerics, Eqs. (48) - (51) and (54),
are independent of animal mass but do depend on ambient pressure.

The scaling relations involving changes in animal mass, which are
derived below, are based on the condition that the animal-parameter
numerics are independent of animal size and thus on the validity of the
similarity relations derived in the last section. However, to derive
the scaling relations involving changes in the ambient pressure it is
necessary to neglect the effect of these changes on the spring-constant,
damping, and the orifice-area numerics mentioned in the previous
paragraph. Having made these approximations, all of the coefficients
of the terms in Eqs. (9) - (12) become constant (independent of ambient
pressure and animal mass) so that if we consider two cases (differing
in animal mass or ambient pressure, or both) where the initial scaled
piston positions ($\underline{X}_1$ and $\underline{X}_2$) and piston velocities ($d\underline{X}_1/d\underline{T}$ and $d\underline{X}_2/d\underline{T}$)
are equal,[*] the corresponding functions $\underline{P}(\underline{T})$, $\underline{V}(\underline{T})$, $\underline{X}_1(\underline{T})$, and $\underline{X}_2(\underline{T})$
will all be equal between the two cases provided only that the input
functions, $\underline{P}'(\underline{T})$, are equal; i.e., if the scaled initial conditions are equal and

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[*] Note that these conditions also require the initial scaled volume ($\underline{V}$)
and rate of change of volume ($d\underline{V}/d\underline{T}$) to be equal.

$$\left[\frac{P'}{P_o} \left(\frac{tP_o^{1/2}}{m^{1/3}} \right) \right]_1 = \left[\frac{P'}{P_o} \left(\frac{tP_o^{1/2}}{m^{1/3}} \right) \right]_2 \tag{55}$$

then

$$\left[\frac{P}{P_o} \left(\frac{tP_o^{1/2}}{m^{1/3}} \right) \right]_1 = \left[\frac{P}{P_o} \left(\frac{tP_o^{1/2}}{n^{1/3}} \right) \right]_2 \tag{56}$$

where the subscripts 1 and 2 refer to the first and second case, respectively.

According to Eq. (56), the internal-pressure numerics as functions of the time numerics are the same for two exposure situations, where the animal masses and /or the ambient pressures are different, provided the scaled pressure-time input parameters are equal as stated in Eq. (55). Examples of the application of these equations to problems in blast biology are presented in Sec. 5.0.

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4.0 EVALUATION OF THE ANIMAL PARAMETERS USED IN THE MODEL EQUATIONS

4.1 General Remarks

An attempt was made to establish reasonable estimates of the model parameters by various methods described below. The set of estimated parameters were then tested by using them in the model equations to compute the thoracic pressure patterns for rabbits exposed to shock-tube blast waves and comparing the results with those obtained experimentally. Adjustments were then made in one or more of the parameters and the comparison was repeated. Several such trials were made until the computed pressure-time patterns corresponded reasonably well with those measured. A summary of the results is presented in Sec. 4.7.

4.2 Lung Volumes and Densities

Results of a study by Crosfill and Widdicombe[45] included measurements of functional residual capacity, tidal volume, and lung mass for seven species of animals. The report also contains data for man taken from other sources.[46, 47]

According to the authors the techniques used to measure the functional residual capacities of the lungs tended to underestimate the true volumes. However, since the same methods were used for all species, the results are valuable for purposes of comparison. Average gaseous volume of the lungs per unit body mass, and average lung density are plotted in Fig. 2 as functions of body mass. (These quantities are defined in the figure.) Note that the data for the mouse, rat, guinea pig, and rabbit are significantly different from those for the monkey, cat, dog, and man. The average of the average lung volumes per unit body mass is 9.08 cm^3/kg for the smaller species and 29.8 cm^3/kg for the larger. However, the average lung density for the small species is almost twice as great as for the large, 0.367 and 0.194 g/cm^3, respectively.

While the data in Fig. 2 are useful in estimating average lung volumes for animals of either the small or the large species, it is evident that scaling between the two groups by body mass would result in gross errors. Average lung densities are used in the next section to help estimate piston areas and masses.

4.3 Geometric Model of the Thorax

In the last section estimates were made for the average gaseous volume of the lungs and average lung density, making it
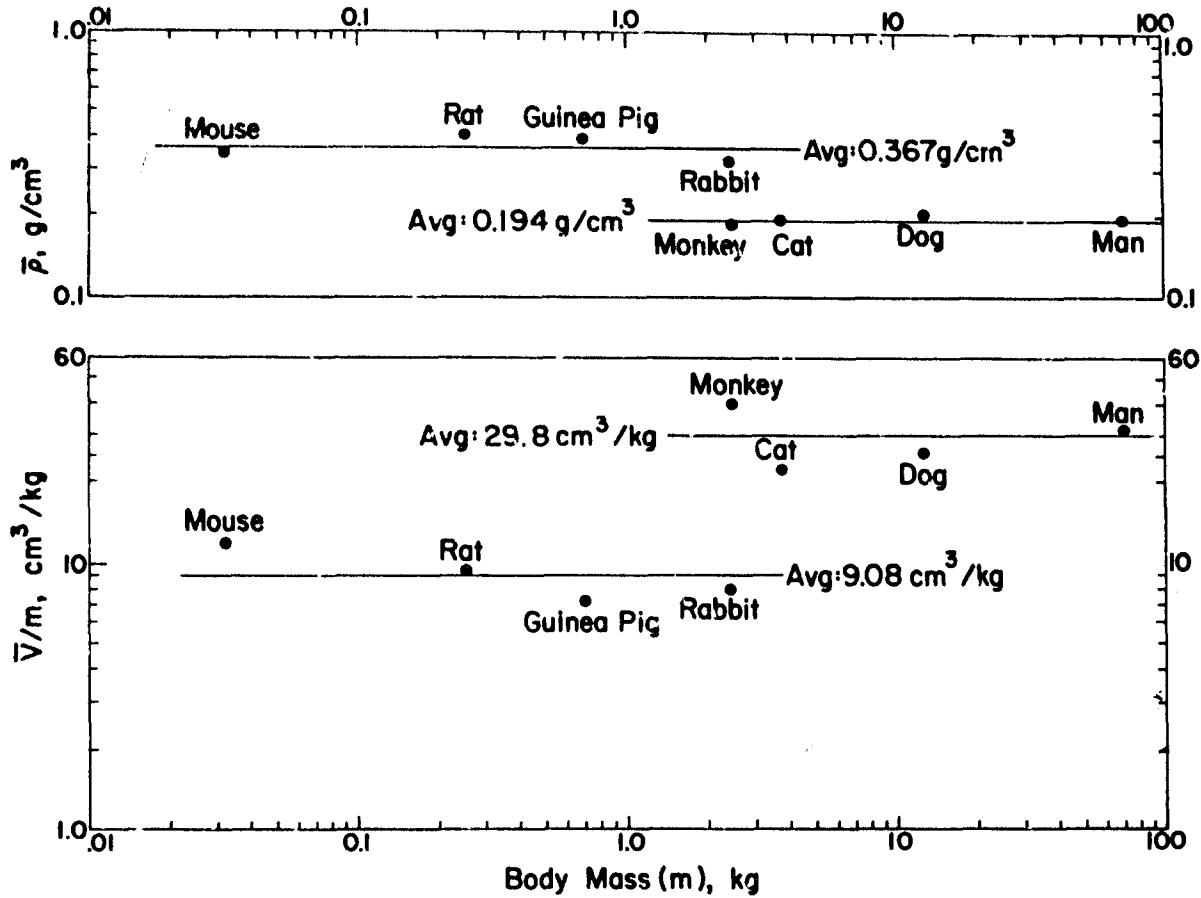
Fig. 2   Average lung volume per body mass and average lung
density as functions of body mass for seven species of
animals and man.   The plots were prepared using data
in Ref 45.   Lung mass as a percent of body mass,
$100M/m = 100\overline{p}\ (\overline{V}/\dot{m})\ /\ (1 - \overline{p})$, is 0.526% for the
small animals and 0.717% for the large ones.

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possible to compute the average total lung volume (gas plus tissue).
In this section an attempt will be made to relate piston areas and
masses with lung volume -- the relation being made more realistic
by idealizing the thorax as a regular geometrical shape.

In a meticulous work, Eycleshymer and Shoemaker[48]
illustrated and described cross-sections of human cadavers at in-
tervals of 2 to 3 cm. The sections passing through the thorax were
used here to determine the cross-sectional areas of the lungs, the
circumferential lengths of contact of the lungs with the rib cage, and
the cross-sectional areas of the rib cage in contact with the lungs.
Note that the last two measurements involve only those portions of
the chest wall which could be expected to move enough under dynamic
loading to reduce the volume of the lungs significantly.

If the cross-sectional areas of the lungs are assumed to be
circular, equivalent diameters can be computed for the measured
areas and also for the measured lengths of contact with the rib cage.
Fig. 3 is a plot of these equivalent diameters for the 9 cross-sections
passing through the lungs. Note that the equivalent diameters based
on each of the criteria increase with height above the lower lobe from
zero to approximately the same maximum values in the region of
the diaphragm. The maximum area of the lung cross-section in this
region (230 cm^3) can be taken here as an approximation of the effect-
ive area of the piston representing the abdomen. The total volume
of the lungs, gas plus tissue, was determined by summing the products
of cross-sectional areas and the distances separating the cross-sections.
Similarly, the products of circumferential lengths and separation
distances were summed to give the total surface area of contact of
lungs with rib cage. These proved to be 2960 cm^3 and 704 cm^2,
respectively.

By trial and error it was found that a 2960 cn^3 right-circular
cylinder whose height is 3/4 of its diameter has the desired area
relations within the accuracy of the measurements. The following
tabulation illustrates the point:

	measured using the cross-sections	computed for right-circular cylinder
V_+, cm^3	2960	2960
A_1, cm^2	230	230
A_2, cm^2	704	691

V_+ is the volume of the gas and tissue in the lungs: A_1,
the area of the abdominal piston, is the area of the base of the cylinder;
and A_2, the area of the chest-wall piston, is the area of the curved
surface of the cylinder. The diameter and the height of the
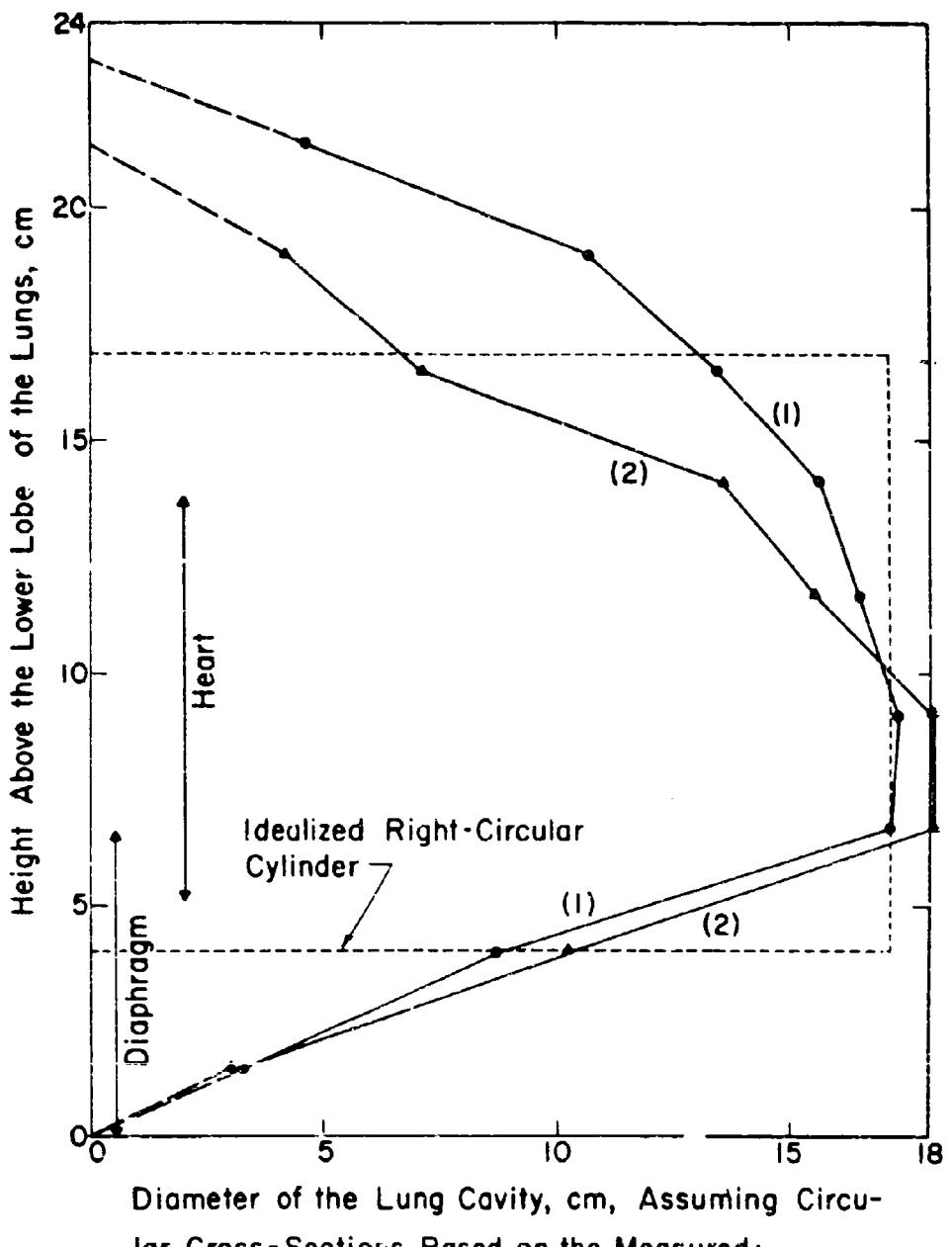
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Fig. 3 The design of a geometric model of the thorax using cross-sectional data for human cadavers reported in Ref 48.

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right-circular cylinder are shown in Fig. 3 as dashed lines.

The volume of the rib-cage tissue adjoining the lungs, measured from the cross-sections and their separations, was 2744 cm^3. Assuming that the tissue had a density of 1 gm/cm^3, the mass, M_2, of the piston representing the chest wall was estimated to be 2744g. For the lack of more definitive information, the abdominal piston was assumed to have the same mass per unit area as the chest-wall piston.

The relations derived above can be expressed as scaling equations to help estimate credible relationships between the gaseous and total volumes of the lungs and the areas and masses of the two pistons taking part in the implosive process.

$$A_1 \quad = \quad 1.117 \, V_+^{2/3} \tag{57}$$

$$A_2 \quad = \quad 3.352 \, V_+^{2/3} \tag{58}$$

$$M_1 \quad = \quad 0.3090 \, V_+ \, \rho_t \tag{59}$$

$$M_2 \quad = \quad 0.9270 \, V_+ \, \rho_t \tag{60}$$

$$V_+ \quad = \quad \bar{V} / (1 - \bar{\rho}/\rho_t) \tag{61}$$

giving

$$A_1/M_1 \quad = \quad A_2/M_2 = 3.615/(V_+^{1/3} \, \rho_t) \tag{62}$$

The symbols used are defined blow.

A_1	:	area of abdominal piston
A_2	:	area of chest-wall piston
M_1	:	mass of abdominal piston
M_2	:	mass of chest-wall piston
V_+	:	average total volume of lung cavity (gas plus tissue)
$\bar{V}$	:	average gaseous volume of lungs, see Fig. 2
$\bar{\rho}$	:	average density of lungs, see Fig. 2
ρ_t	:	tissue density, assumed to be 1 gm/cm^3

Note that the areas and masses in Eqs. (57) - (62) are scaled with the average total lung volume (a function of average gaseous volume, average lung density, and tissue density) rather than with body mass. This procedure facilitates use of the scaling data in Fig. 2 for the two distinct groups of species.

4.4   Spring Constants

Velocity resonant frequencies have been measured for cats,[41,42]

* See discussions in Secs. 2.1 and 6.0.

and dogs[43] by introducing sinusoidal waves into the airways via the trachea or by exposing the whole animal to oscillating pressures in a closed chamber with a tracheal tube connected to measuring devices outside the chamber. In either case the forcing frequencies were varied to determine that frequency which would produce either maximum chest-wall velocity or maximum air velocity. The velocity resonant frequency is defined by the following equation:

$$f_v = \sqrt{K/M}/(2\pi) \qquad (63)$$

where f_v is the frequency producing the maximum velocity response, K is the spring constant with units of force per unit displacement, and M is the mass moved.

The response due to motion of the chest wall was not separated from that due to motion of the diaphragm and abdomen, i.e., a single resonant frequency was determined for each animal. Thus, to apply these data to the model parameters, M in Eq. (63) would represent the mass of either of the pistons and K the corresponding spring constant. Since mass per unit area was assumed to be the same for the two pistons (see Sec. 4.3), the spring constant per unit area would also be the same if the pistons have the same resonant frequency.

To make the resonant frequency data for cats and dogs more generally applicable, it is necessary to determine a mass-scaling relation. According to Eqs. (35) and (36), the spring constant varies as the cube root of the animal mass, and referring to Eqs. (28) and (29) the vibrating masses vary directly as the body mass. Applying these relations to Eq. (63), the following is obtained

$$f_v m^{1/3} = \sqrt{C_8/C_3}/(2\pi) = \sqrt{C_9 C_4}/(2\pi) = C_{12} \qquad (64)$$

where m is the body mass and C_{12} is a constant.

Eq. (64) was used to normalize the resonant frequency data from references 41, 42, and 43. The results are shown below:

Animal	f_v $\mathrm{sec^{-1}}$	m kg	$f_v m^{1/3}$ $\mathrm{g^{1/3}/sec}$	Ref.
cat	9.6	2.50	130	41
cat	11.5	2.76	161	42
dog	5.4	12.	124	43
Avg.			138	

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Making use of Eqs. (63) and (64), the following scaling equations are obtained by equating $f_v m^{1/3}$ to the average experimental value of 138 $g^{1/3} sec^{-1}$:

$$K_1 / M_1 = K_2 / M_2 = 751,800 / m^{2/3} \qquad cgsu \qquad (65)$$

The subscripts 1 and 2 refer to the abdominal and chest-wall pistons, respectively.

4.5 Effective Orifice Area

Results of rapid-decompression tests on a 83-kg man were reported by Luft and Bancroft.[49] Using an analytical technique developed by Haber and Clamann[50], the authors evaluated an average effective orifice diameter of 0.478 cm. By applying Eq. (30) and (31), the following scaling relation is obtained for the effective orifice area.

$$A_h = 9.43 \times 10^{-6} m^{2/3} \qquad cgsu \qquad (66)$$

4.6 Damping Factors

Experiments in blast biology[51] produced records of pressures in the thorax of animals exposed to blast waves generated by a shock tube. Two such records are shown in Figs. 4 and 5. In each of the experiments a small pressure transducer was inserted in the esophagus of a 1.8-kg rabbit down to the level of the heart. The animal was then placed in a cage bolted side-on against the end-plate closing the shock tube. In each case, the upstream side of the animal "felt" the incident shock of about 7-psi overpressure followed by the reflected shock approximately 0.5 msec later -- the travel time of the shock wave across the animal to the reflecting surface and back again. However, the side of the animal against the end-plate "felt" the incident and the reflected shocks almost simultaneously. The time step used in the computations was the average of those for the limiting cases mentioned above; viz, 0.25 msec, representing the time separation of the incident and reflected shocks at a distance from the end-plate equal to that of the center of the thorax.

The internal-pressure records described above are characterized by damped oscillations and were used to estimate damping factors. For analytical reasons it was necessary to assume a linear-spring system even though the "air spring" of the lung model makes the system non-linear.*

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* See discussion in Section 3.2
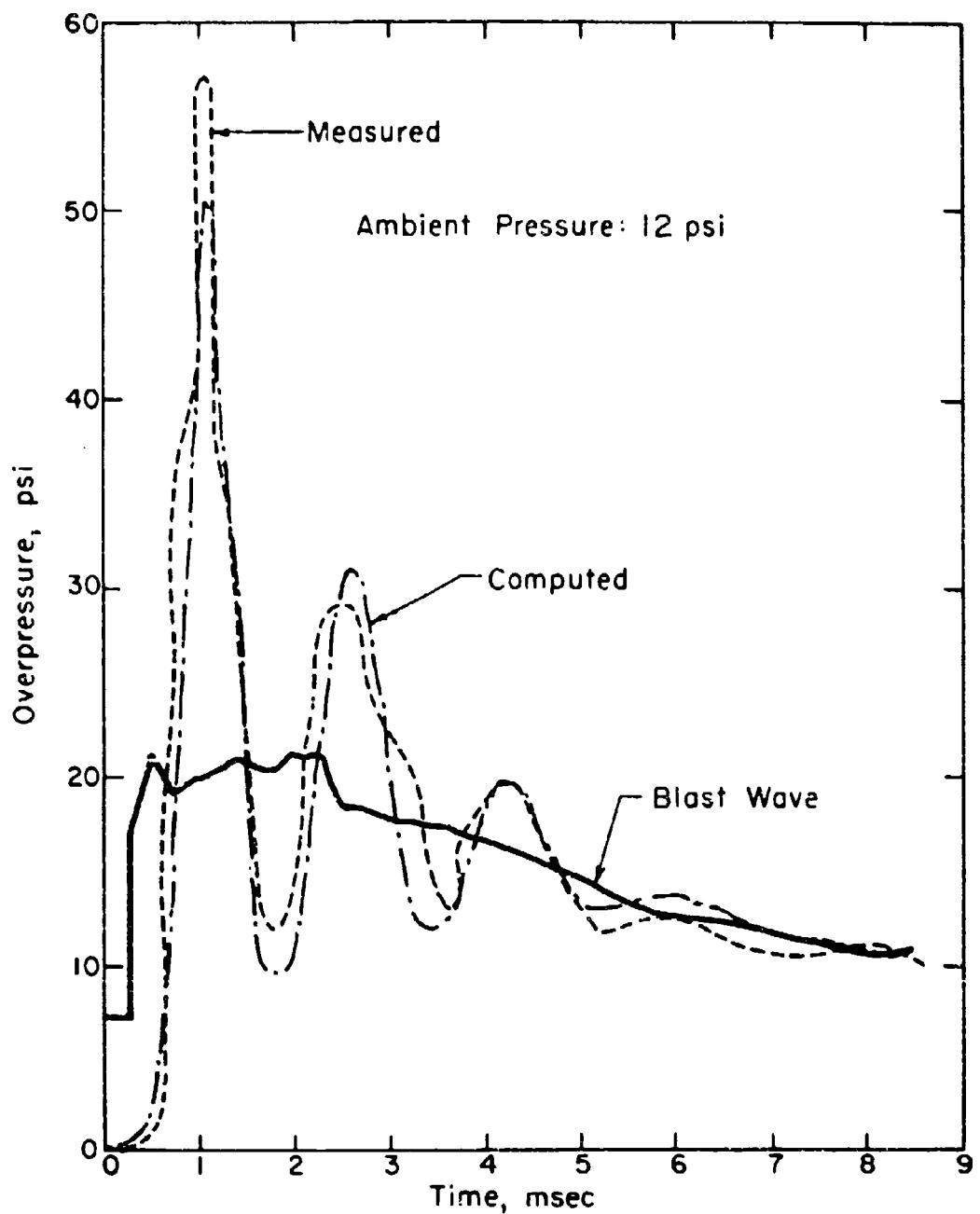
Fig. 4   Thoracic overpressures measured[51] and computed for a
1.8-kg rabbit exposed near the closed end of a shock tube to
the indicated blast wave.   The adjusted parameters used in
the lung-model computations are listed in Table 1.
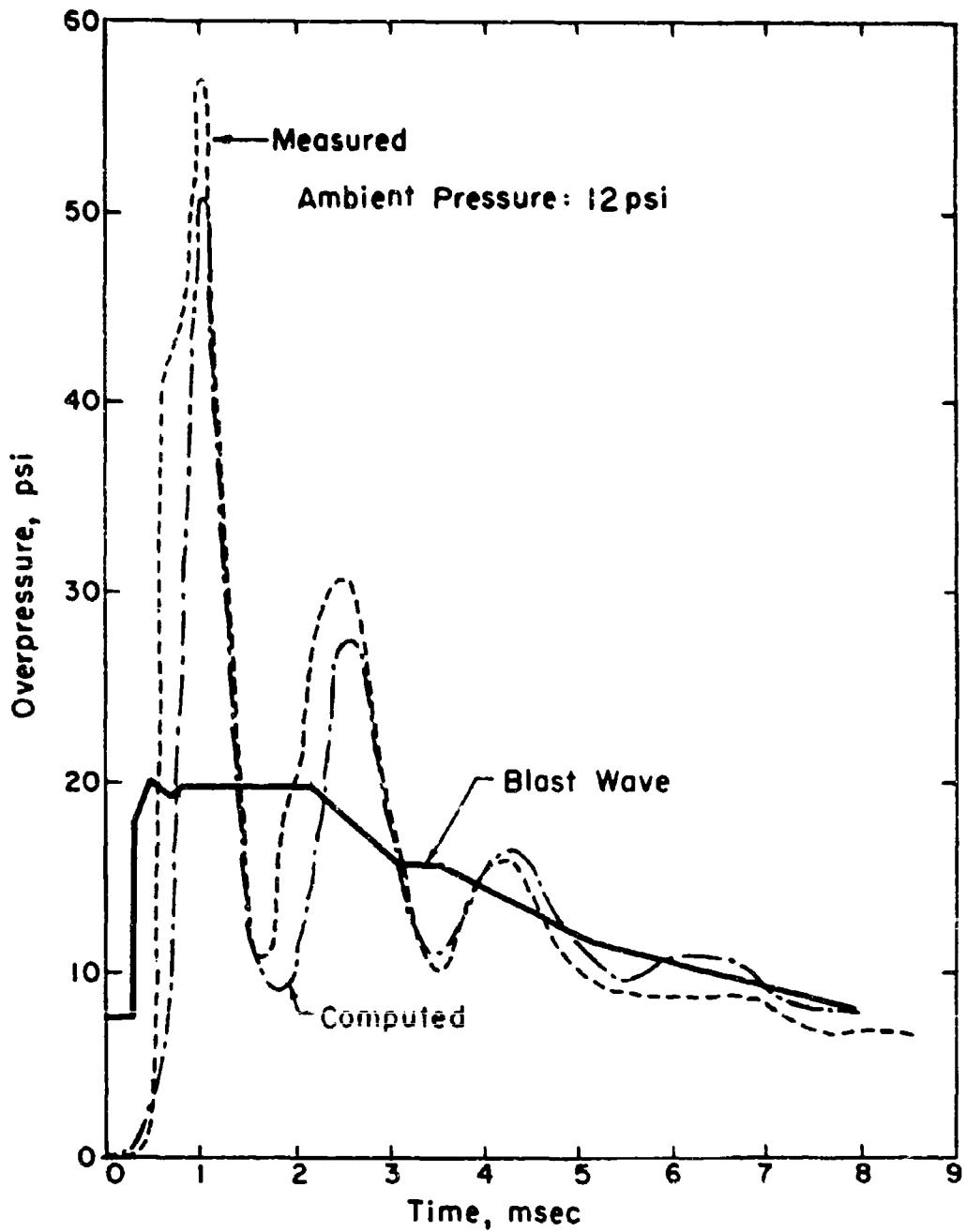
Fig. 5 Measured and computed thoracic pressures for a 1.8-kg
rabbit. The exposure conditions and the animal parameters
are the same as those stated for Fig 4.

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According to linear theory the formula for the damping relation is^{52}

$$a = \frac{\ln (x_n/x_{n+1})}{2\pi} \left[1 + \ln^2 (x_n / x_{n+1}) / (4\pi^2) \right]^{-1/2} \tag{67}$$

where a is the ratio of the damping factor to the critical damping factor, x_n and x_{n+1} are the amplitudes of two consecutive vibrations, and $\ln$ indicates the logarithm to the base e.

Information available at this time will not allow the effects of the two pistons (abdominal and chest-wall) to be distinguished from each other. Thus the simple assumption was made that the pistons move as **one**; i.e., their respective displacements are identical at any point in time provided, of course, that their initial displacements and velocities are the same. Examination of the model equations, (7) and (8), shows that the conditions for the two pistons to move as one[*] are that $K_1/M_1 = K_2/M_2$, $A_1/M_1 = A_2/M_2$, and $J_1/M_1 = J_2 M_2$. The first two conditions were dealt with in previous sections (4.4 and 4.3), and the third one is recognized in the material that follows.

In order to use Eq. (67) it is necessary to express the displacement amplitudes in terms of peak pressures which were measured. Neglecting air flow, the polytropic pressure-volume changes of the lung can be expressed as

$$x = V_0/A \left[1 - (P_0/P)^{1/\gamma} \right] \tag{68}$$

where x is the displacement of each of the pistons with total area A when the cavity pressure (absolute) is P, V_0 is the initial volume of the cavity when the internal pressure is P_0 and the piston displacement is zero, and γ is the polytropic exponent assumed to be 1.2.

Data for the first two peaks of the measured internal pressure records shown in Figures 4 and 5 were used in Eqs. (67) and (68) to evaluate damping ratios. The succeeding peaks could not be used since the blast pressures were decaying appreciably after the second peak. Damping ratios of 0.149 and 0.130 were evaluated for the data in Figs. 4 and 5, respectively, while the internal pressure was oscillating about an external over-pressure of approximately 20 psi in each case.

The average value (0.1395) of the damping ratios mentioned above were used in Eq. (43) along with animal parameters previously estimated; the total damping factor thus determined for the 1.8-kg rabbits was 37,100 dynes-sec/cm. As mentioned above, damping

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[*]   The single piston equivalent to the two-piston system has parameters equal to the sum of those for the two pistons; i.e., M_1+M_2, A_1+A_2, etc.

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was apportioned to each of the pistons according to its mass, resulting in the following scaling relation.

$$J_1 / M_1 = J_3 / M_3 = 14170/m^{1/3} \qquad \text{cgsu} \qquad (69)$$

where J_1 and J_3 are damping factors for the abdominal and chest-wall pistons of mass M_1 and M_2, respectively and m is the animal body mass.

4.7 Summary of Estimated and Adjusted Parameters

It was shown in previous sections that the body-mass scaling of most of the animal parameters depends on the species type. Evidence was presented of at least two types: the mouse, rat, guinea pig, and rabbit being members of the small-species type and the monkey, cat, dog, and man, members of the large-species type.

Estimated model parameters scaled to an idealized 1-kg animal are listed in the first two columns of Table 1 for the two types of species. The parameter which differs greatest between the two types is that of average lung volume, the large-species type having an average volume more than three times as great as that for the other. It is not significant that the estimated orifice areas are the same for the two types since they were both scaled according to body mass from data obtained for man;[49] additional information will probably indicate they are actually different.

The third column of Table 1 lists the model parameters scaled to a 1.8-kg small-species animal. The last column of the table contains the "adjusted" values of the parameters obtained by attempts to match the output of the model to experimental records of pressure in the thorax of 1.8-kg rabbits during blast experiences. (See Sec. 4.6) The pressure-time curves marked "computed" in Figs. 4 and 5 were obtained using these adjusted parameters.

Table I SUMMARY OF ESTIMATED AND ADJUSTED MODEL PARAMETERS

| | Estimated for 1-kg Animal | | 1.8-kg Rabbit | | Reference |
	"Small" Species	"Large" Species	Estimated	Adjusted	
$\bar{V}$, cm^3	9.08	29.8	16.3	16.3	Fig 2
A_1, cm^2	6.59	12.4	9.74	8.78	Eqs (57) (61)
A_2, cm^2	19.8	37.2	29.2	26.3	Eqs (58) (61)
M_1, g	4.43	11.4	7.96	7.04	Eqs (59) (61)
M_2, g	13.3	34.3	23.9	21.1	Eqs (60) (61)
K_1 dynes/cm	33,300	85,700	40,400	39,900	Eq (65)
K_2 dynes/cm	100,000	258,000	121,000	120,000	Eq (65)
A_h cm^2	0.00943	0.00943	0.0140	0.0140	Eq (66)
J_1, dynes-sec/cm	6,280	16,200	9,275	6,570	Eq (69)
J_2, dynes-sec/cm	18,800	48,600	27,825	19,700	Eq (69)

Definitions

$\bar{V}$: Average gaseous volume of the lungs
A_1 : Area of piston representing the abdomen
A_2 : Area of piston representing the chest wall
M_1 : Mass of piston representing the abdomen
M_2 : Mass of piston representing the chest wall
K_1 : Spring constant for the piston representing the abdomen
K_2 : Spring constant for the piston representing the chest wall
A_h : Effective area of the orifice representing the airways
J_1 : Damping factor for the piston representing the abdomen
J_2 : Damping factor for the piston representing the chest wall

5.0   APPLICATIONS TO PROBLEMS IN BLAST BIOLOGY

5.1   Restatement of the Scaling Equations

The scaling equations derived in Sec. 3.3 for similar animals, (55) and (56), apply to both the external and internal pressure waves as functions of time. For convenience in making specific applications, the equations are written below in terms of characteristic pressures and times used to compare pressure waves of the same shape. (Pressure waves are considered to be of the same shape if one can be derived from the other by multiplying the pressures and the corresponding times by constant factors, a pressure factor and a time factor.)

$$P'_2 / (P_o)_2 = P'_1 / (P_o)_1 \tag{69}$$

$$t_2 (P_o)_2^{1/3} / m_2^{1/3} = t_1 (P_o)_1^{1/3} / m_1^{1/3} \tag{70}$$

$$P_2 / (P_o)_2 = P_1 / (P_o)_2 \tag{71}$$

where the subscripts 1 and 2 refer to two blast situations where the blast parameters and/or the animal body masses are different. The parameter definitions are:

P' :   Any characteristic pressure of blast waves of similar shape. Usually the peak pressure is used to compare two different blast waves.

P_o :   Ambient pressure, also assumed to be the initial gaseous pressure in the lungs.

P :   Any characteristic pressure of the pressure pulse occurring in the lungs. The peak lung pressure is used in this study.

t :   Any characteristic time of blast waves of similar shape, or of the internal pressure waves; e.g., duration of the blast wave, time to reach maximum pressure in the animal lungs, etc.

m :   Body mass of similar animals. See Sec. 3.2

5.2   Index of Biological Response

In the design of the model the input numerics J_1, J_2, K_1, K_2, A_1, A_2, A_h, and P (T) were assumed to be all the significant parameters needed to describe the gross response of the thoraco-abdominal system to rapid changes in environmental pressure. Having made this assumption, it follows from dimensional analysis that any

nondimensional index of biological response R (e. g. , percent mortality, percent increase in lung mass, etc.) is a function only of the numerics listed. Thus, letting the bracket subscripts 1 and 2 refer to two blast situations where the blast parameters and/or the animal body masses are different, it can be stated that

$$[R]_1 = [R]_2 \tag{72}$$

if $\quad [J_1]_1 = [J_1]_2, \quad [J_2]_1 = [J_2]_2, \quad [K_1]_1 = [K_1]_2,$

$[K_2]_1 = [K_2]_2, \quad [A_1]_1 = [A_1]_2, \quad [A_2]_1 = [A_2]_2,$ and

$[A_h]_1 = [A_h]_2,$ as was assumed in Sec. 3.3 in deriving

scaling equations (55) and (56) for similar animals; and if $[P'(T)]_1 = [P'(T)]_2;$ i. e. , if Eqs. (69) and (70) are satisfied.

Note that the above analysis does not indicate specific mechanisms but only the relations between the significant physical parameters influencing biological response; however, mechanisms may be postulated by interpretation of Eqs. (69) - (72). Subject to the restrictions previously discussed, two mammals exposed to different blast situations will have equal biological response, Eq. (72), if the conditions of exposure satisfy Eqs. (69) and (70). Thus, referring to Eq. (71), the ratio of the peak internal pressure to the ambient pressure (P/P_0) could be the critical factor to the animal; however, it should be noted that this ratio is approximately proportional to the ratio of the initial lung volume to the minimum volume (V_0/V), a measure of tissue distortion. Another critical factor could be the ratio $\Delta P/P_0$ where ΔP is the difference between the peak internal pressure and the simultaneous external pressure, and P_0 is the ambient pressure. The factors which are critical in producing biological damage from air blast may be determined more precisely in future investigations.

5.3 Long-duration Blast Waves

Six species of animals (mouse, rat, guinea pig, rabbit, dog, and goat) were used in one shock tube study[16] and two species (hamster and cat) in another[51] to determine biological tolerance to sharp-rising blast waves of "long" duration (400 msec). Except for the dogs and goats which were secured with harness and straps, the animals were exposed in wide-mesh cages against the reflecting surface at the end of the shock tube. Thus, the upstream side of the creature felt the incident wave first and a short time later the reflected wave. The length of this time-step would be approximately proportional to the body width of the animal or to the cube root of the body mass. Thus, by Eq. (70), the effect of the time step would be identical for (similar) animals of all body masses

Examination of the measured pressure-time records[16] reveals that the blast pressures were approximately constant during the time

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of interest, i.e., the first few milliseconds required for the internal pressures to reach a maximum value. Therefore, the effective durations were infinite and could have no distinguishing effect on animals of different masses; i.e., referring to Eq. (59), infinity divided by $m_2^{1/3}$ cannot be distinguished from infinity divided by $m_1^{1/3}$.

It was shown above that the time parameters of the blast waves used satisfied Eq. (70) for similar animals of any body mass. Ambient pressure was not varied during the experiments; therefore, according to Eqs. (69) and (72), a given peak blast pressure would result in the same value of the index of biological response for similar animals of any body mass. Thus, the blast overpressure producing 50% mortality should be independent of body mass if the animal species are similar.

The experimental data from references (16) and (51) which are plotted in Fig. 6 suggest that the animals are actually divided into two groups, one composed of the smaller species (mouse, hamster, rat, guinea pig, and rabbit) and the other composed of the larger species (cat, dog, and goat). Statistical tests described in the following paragraph were made to determine if animal mortality within each of the groups is significantly dependent on body mass.

Assuming that the P_{bo} values plotted in Fig 6 were determined with the same reliability, least-square regression equations of the form

$$\log P_{bo} = a + b \log m$$

were determined for the small-animal data and for the large-animal data. The slopes, b, were examined by the t-test to determine the probability P_b of obtaining by chance absolute values of b as large as, or greater than, those observed assuming that the true value is zero. The regression coefficients a and b are listed below along with values of $(1 - P_b)$, the probability that P_{bo} is dependent on animal mass.

	a	b	$(1 - P_b)$
Small-animal data:	1.5061	.005206	.19
Large-animal data:	1.6060	.01804	.78

Since, as shown above, animal mortality within each of the groups is not significantly dependent on body mass, the P_{bo} data were average to obtain 31.9 psi for the small animals and 48. 1 psi for the larger ones. These groupings are consistent with the lung-volume and lung-density data plotted in Fig. 2 which indicate that mouse, rat, guinea pig, and rabbit are members of one group and monkey, cat, dog, and man, members of another. (No data were shown for the hamster and the goat.)

5.4 Long-Duration Blast Waves with a Time Step

In other experiments[18] small animals were placed in wide-mesh cages and exposed side-on at the end-plate of a shock tube and at various

P₅₀ : Reflected Overpressure Producing 50% Mortality When The Animal
Was Against The End-Plate Of The Shock Tube

Ambient Pressure: 12 psi

Mouse

Hamster

Rat

Avg: 48.1 psi

Cat

Guinea
Pig

Rabbit

Avg: 31.9 psi

Goat

Dog

~70kg
52.3 psi

Regression Equation: $\log P_{50} = 1.5753 + 0.07755 \log m$

Body Mass (m), kg

P_{50}: psi
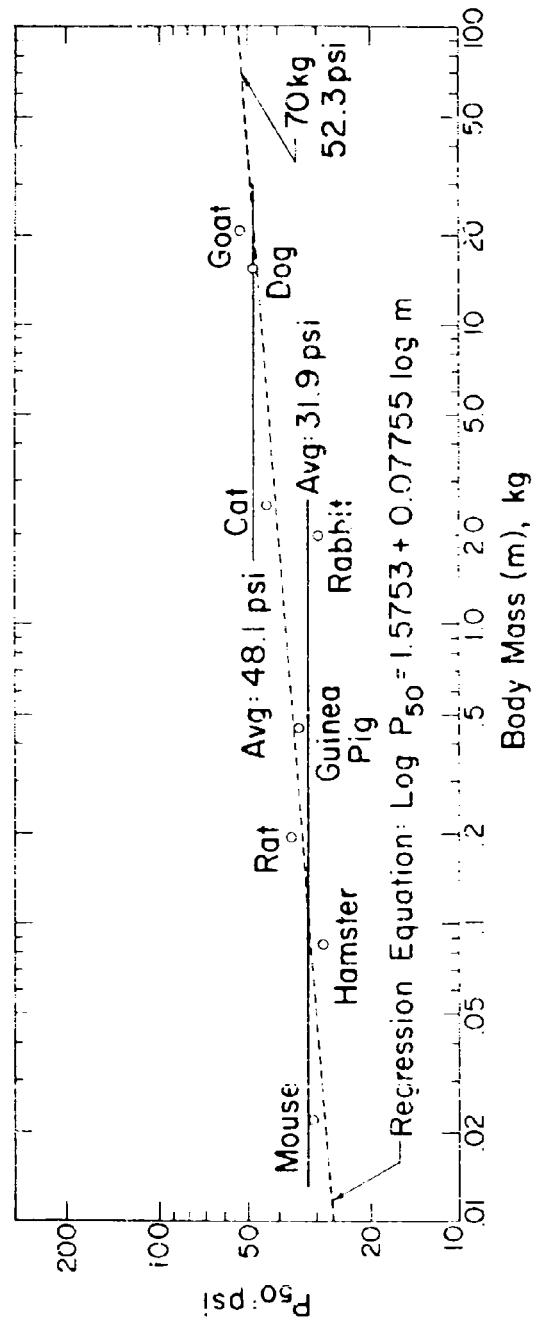
Fig. 6 A test of animal similarity: Maximum reflected overpressure of 400 msec blast waves vs. animal body mass for the condition of 50% mortality. The animals were exposed against the end-plate of the shock tube to fast-rising waves with practically constant overpressure for the time necessary for the animal's intra-thoracic pressure to reach maximum value. According to the scaling equations the response of similar animals to a given blast wave of this type would be identical. (Data from Ref 16 and 51)

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distances up to 12 in. away from it. An attempt was made to produce incident and reflected shock waves of constant magnitude by using approximately the same overpressure in the compression chamber. The reflected overpressures measured for the entire series of shots varied from 48 to 56 psi, the average being 52.1 psi. The corresponding average of the incident shock overpressures was between 17 and 18 psi, spanning the 17.2 psi shock that theoretically would produce a reflected wave of 52.1 psi for the conditions of perfect reflection at normal incidence and an ambient pressure of 12 psi.

Animal mortality vs. distance from the end-plate were reported for the mouse, rat, guinea pig, and rabbit. All animals placed against the end-plate were killed but the mortality showed a decline as the distance from the end-plate was increased -- the distance necessary to afford a given degree of protection being greater for the large animals than that for the small ones.

Scaling equation (69) was satisfied since the average blast overpressures (incident and reflected) were approximately the same for all species. The biological-response numerics, Eq. (72), would be the same for all species if the time numerics, described in Eq. (70), were the same. The characteristic times significant to these experiments were, of course, the times between the incident and reflected blast waves. Thus, according to Eq. (70), (time step) / (body mass)$^{1/3}$ is predicted to be constant for all species for a given index of biological response, Eq. (72). (Note that ambient pressure was not varied in these experiments.)

The scaling concepts presented above were applied to the experimental data by plotting in Fig. 7, for each species, scaled time step vs. body mass for the condition of 50% mortality. The average scaled time step for the mouse, rat, guinea pig, and rabbit, was found to be 0.516 msec/kg$^{1/3}$, applicable to the experimental conditions described. The plotted data, Fig. 7, indicate no dependence of the scaled time steps on body mass and thus demonstrate, within reasonable limits, the similarity of these species of animals.

In the preceding paragraphs the scaling of a time parameter of the blast wave with animal body mass was demonstrated; however, nothing was said in regard to the mechanisms involved in reducing mortality by moving the animals away from the reflecting surface. To help explain these mechanisms, numerical solutions were obtained for appropriate blast waves using the model equations and the adjusted animal parameters listed in Table 1 scaled to a 1.7-kg rabbit, the average mass of the rabbits used in the experiment described above. Model solutions are shown in Fig. 8 for the situation of the animal cage being against, and at three noted distances away from, the end-plate which situations were associated with 100, 80, 12, and 0 percent mortality, respectively.*

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* The time between the incident and reflected shock in Fig. 8(a) corresponds to the travel time of the blast wave from the midpoint of the animal cage to the reflecting surface and return.

31
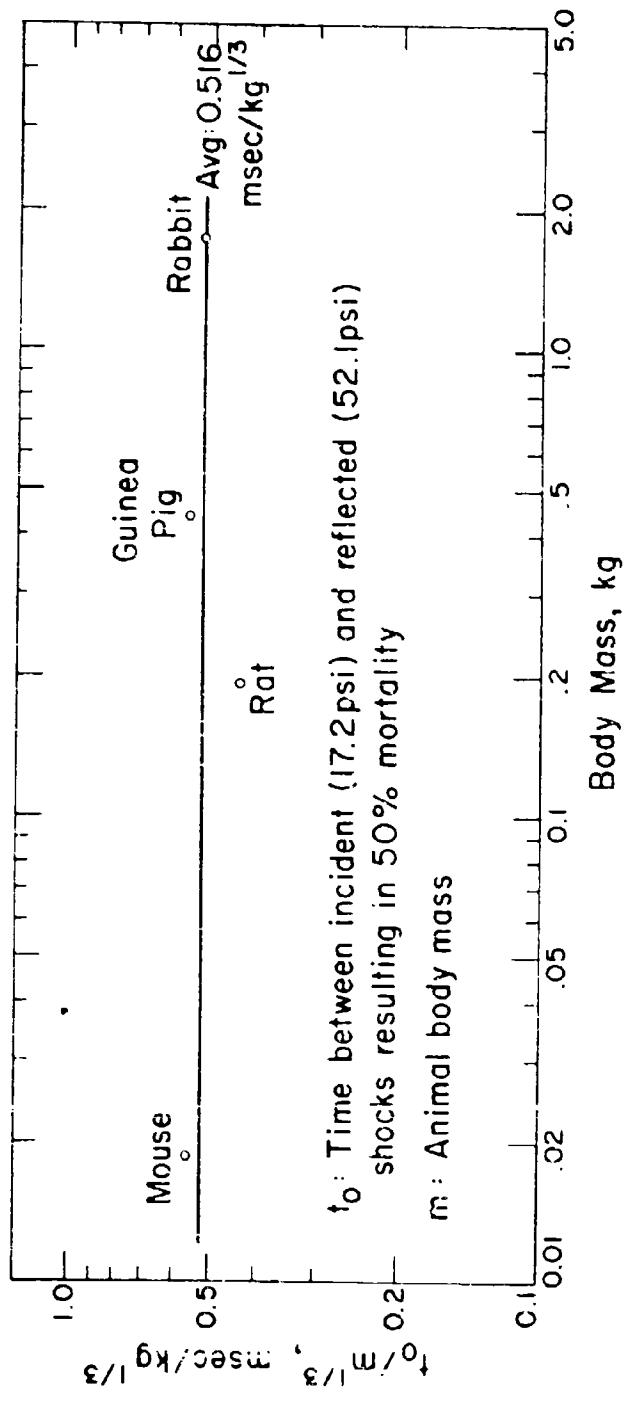
Fig. 7 A test of body-mass scaling for similar animals. The plotted data show that the four species of animals have approximately the same sensitivity to time separations of the incident and reflected shocks which are proportional to the cube root of body mass. (Data from Ref 18)

The chart contains:

- Y-axis: $t_o/m^{1/3}$, msec/kg$^{1/3}$ (values 1.0, 0.5, 0.2, 0.1)
- X-axis: Body Mass, kg (values 0.01, .02, .05, 0.1, .2, .5, 1.0, 2.0, 5.0)
- Mouse
- Rat
- Guinea Pig
- Rabbit
- Avg: 0.516 msec/kg$^{1/3}$

t_o: Time between incident (17.2 psi) and reflected (52.1 psi) shocks resulting in 50% mortality

m: Animal body mass
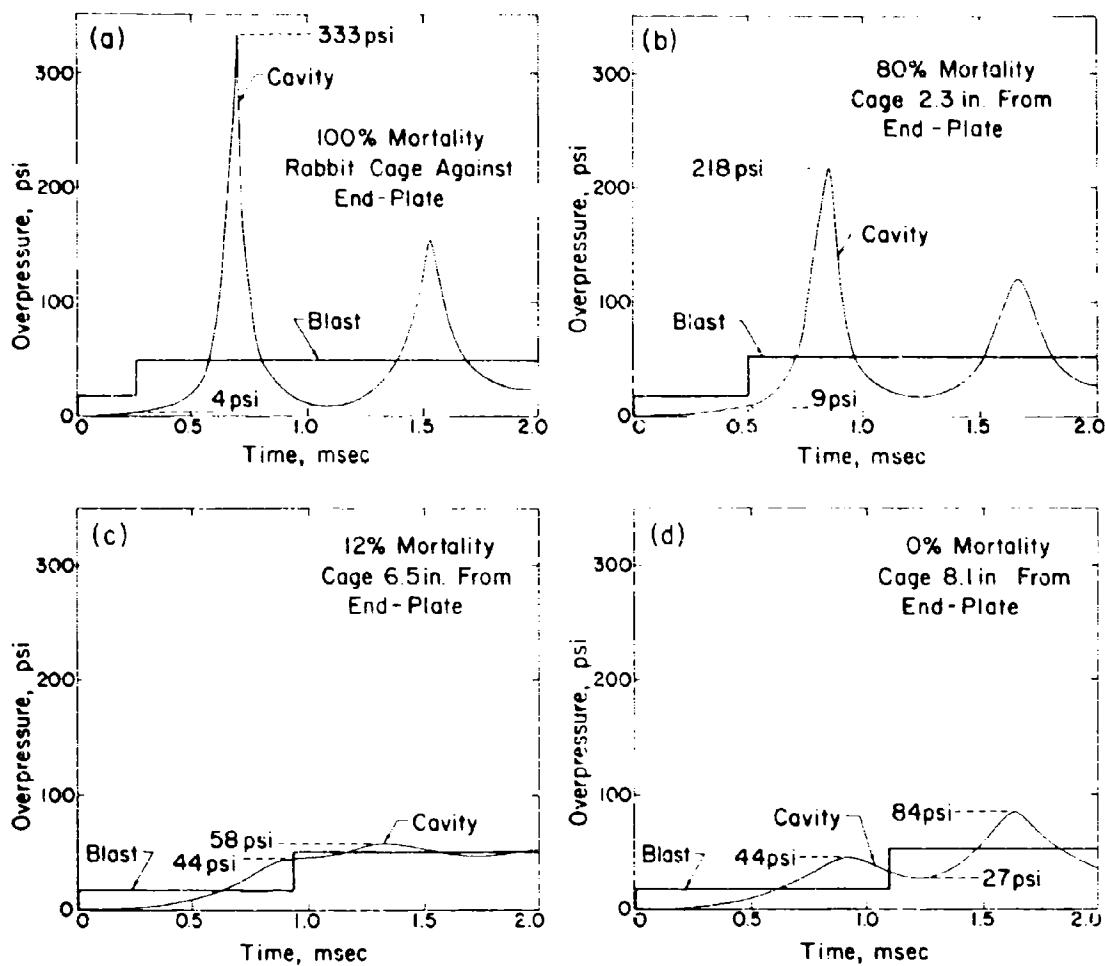
Fig. 8 Computed cavity, or thoracic, overpressure vs. time for 1.7-kg rabbits exposed at various distances from the end-plate of the shock tube. The incident and reflected shocks were 17.2 and 52.1 psi, respectively. The mortality data shown are from Ref 18.

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Note for the four blast situations that the peak cavity pressure is inversely related to the minimum cavity pressure occurring after the arrival of the reflected shock, i.e., cavity pressure resulting from the incident wave "inhibits" the effect of the reflected wave. The computed data in Fig. 8(c) show that the cavity pressure had reached a maximum value of 44 psi at the time the reflected shock of 52.1 psi arrived and that the subsequent peak cavity pressure was only 58 psi. At the other extreme, the data in Fig. 8(a) indicate that the cavity pressure was 4 psi when the reflected wave arrived which resulted in a peak cavity pressure of 333 psi.

Two reasons are proposed to account for the reduced mortality when the animal is moved away from the reflecting surface. (1) The driving pressure (the difference between the external and internal pressure) of the reflected shock is reduced because of the increased pressure in the lungs. (2) The increased internal pressure also re-sults in a stronger air spring* being active at the time of arrival of the second pulse and tends to inhibit further motion of the chest wall and abdomen. These effects are maximized -- the animal is most protected -- if the reflected shock arrives at the time when the lung pressure has reached a peak value due to the incident wave. Compare Figs. 8(b), 8(c), 8(d).

5.5 Dog and Goat Blast Data Scaled to a 70-kg Mammal and from 12.0- to 14.7- psi Ambient Pressure**

Reference 10 contains a summary of the results of experiments in which dogs and goats were exposed against reflecting surfaces*** to blast waves generated in shock tubes and by high explosives. The average atmospheric pressure at the experimental station was 12.0 psi. Maximum overpressures and the corresponding blast-wave durations were reported for the condition of 50% mortality within 24 hours after exposure.

Tolerance to similar blast situations, but at sea-level atmos-pheric pressure, was estimated for a 70-kg mammal by applying the scaling equations presented in Secs. 5.1 and 5.2 to the experimental data. (These would also be reasonable estimates for man to the degree that his thoracic structure is similar to that of the experimental animals. See Sec. 4.2). The index of biological response, Eq. (72), remains constant if Eqs. (69) and (70) are satisfied. Thus, applicable to the data for both dogs and goats,

$$P'_2 = P'_1 (14.7/12.0) \qquad (73)$$

where P'_2 is blast pressure for an ambient pressure of 14.7 psi if P'_1 is the blast pressure determined for 12.0 psi.

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*   See Sec. 3.2 .

**   Experimental evidence of the effects of ambient pressure on the tolerance of mice to air blast can be found in Ref. 53.

***   Note that this type of exposure minimizes the wind effect.

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Scaled from the data for the 16.5-kg dogs, blast wave duration is defined by

$$t_2 = t_{1d} (70/16.5)^{1/3} (12.0/14.7)^{1/2} \tag{74}$$

and for the 22.2-kg goats

$$t_2 = t_{1g} (70/22.2)^{1/3} (12.0 \cdot 14/7)^{1/2} \tag{75}$$

where t_2 is duration applicable to a 70-kg mammal and an ambient pressure of 14.7 psi if t_{1d} and t_{1g} are durations for dogs and goats, respectively, where the ambient pressure is 12.0 psi.

The original and the scaled data are plotted in Fig. 9. The smooth curve is an eye-fit of the data scaled for the 70-kg mammal and to sea level conditions. The consistancy of the results is naturally worthy of comment and may be of considerable importance in estimating human tolerance to blast overpressures. This is probably true if it turns out that man responds more like the "larger" than the "smaller" mammalian species.

Estimate of the Parameters of Reflected Blast Waves Resulting in
50% Mortality of 70 Kg Mammals at 14.7 psi Ambient Pressure

⊚ Scaled from experimental data for 16.5 Kg
dogs at 12.0 psi ambient pressure

▲ Scaled from experimental data for 22.2 Kg
goats at 12.0 psi ambient pressure

• Original data

High Explosives ← | → Shock Tube
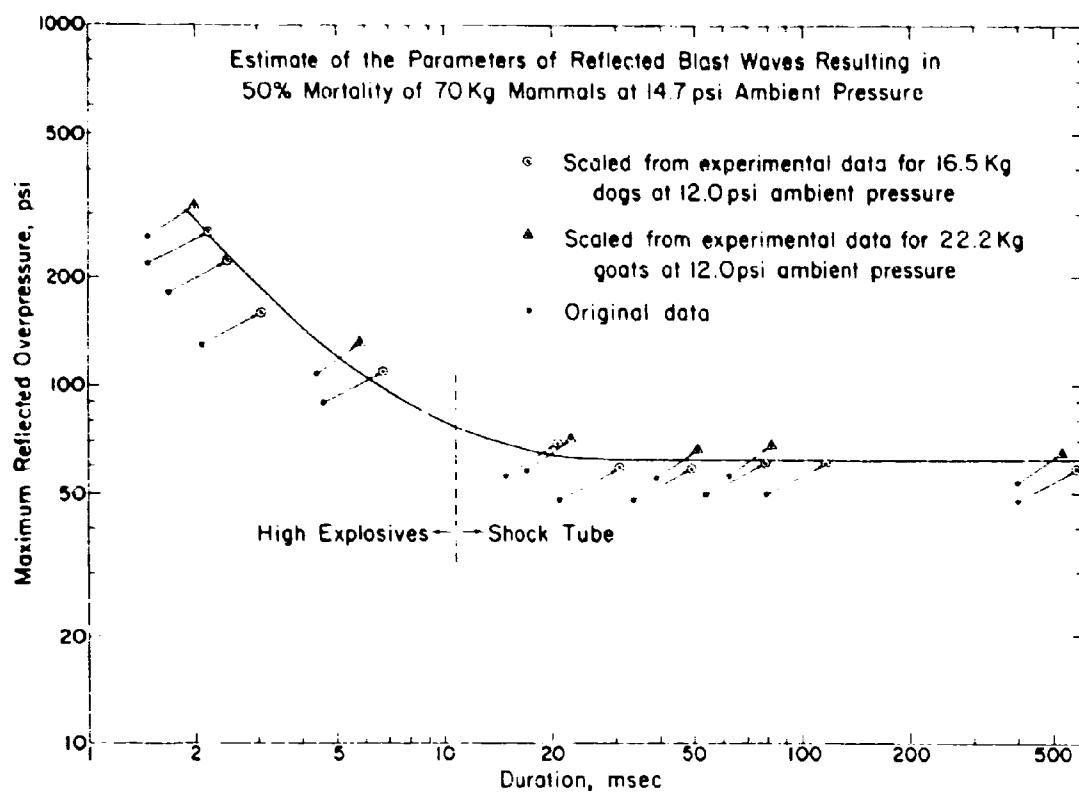
Fig. 9   An example of body-mass and ambient-pressure scaling
using experimental data from Ref 10.   The smooth curve is an
eye fit of the dog and goat data scaled to a 70-kg mammal and to
14.7 psi ambient pressure.   The following readings were taken
from the curve:

2 msec	290 psi
3 msec	188 psi
5 msec	120 psi
10 msec	79 psi
20 msec	64 psi
30 msec	62 psi
400 msec	62 psi

6.0   DISCUSSION

6.1   General

In general it is well to emphasize that the present study represents an exploratory effort to bring theory and experiment together with the objective of trying to understand more fully the mechanisms that are responsible for primary air blast injury. The attempt at integrating physical, biophysical and biological factors suffers not only because of "state-of-the-art" limitations, conceptual and technical, but also because necessary information is simply not yet available even though some of it could be obtained making use of appropriate experimental procedures.

It is an encouraging matter that the complex thoracic and abdominal portions of the body can, for the purpose of helping visualize the effects of blast loading, be viewed simply as a gas-filled box to which are attached an orifice and two pistons to simulate flow in the airways and the movement of the chest wall and the diaphragm, respectively. It is not surprising that the somewhat tedious mathematical and analytical formulations were made, programmed, and that actual model solutions were computed. What is more significant, however, is that considerable progress was made not only in defining the parameters of the fluid-mechanical model conceived, but in actually obtaining values that are reasonable for the several individual parameters. Though these are admittedly approximations, it was nonetheless true that only relatively small adjustments were needed to obtain satisfying agreement between computed and measured thoracic pressures in the instances described for rabbits exposed to shock tube generated blast waves. While such results suggest that the parameter values have a much better-than order-of-magnitude reliability at the present time, it should be candidly stated that there is much yet to be done in adding sophistication to improve accuracy in the approach taken.

The model described might have been formulated using one piston rather than two. Since the parameters estimated for the two pistons were such that they act as one; i.e., their time displacement histories were identical for a given blast experience. Although this is unlikely to represent the "real-life" situation, presently available information does not allow the action of the abdomen to be differentiated from that of the chest wall. However work already planned with the model requires a two-piston system.

6.2   The Geometric Model of the Thorax

A geometric model of the thorax was formulated to help estimate realistic relations between the gaseous volume of the lungs and (1) the area of the pleural surface and (2) the mass of the chest wall tissue which moves in the blast-induced implosion process. While the right circular cylinder with a height three-quarters of its diameter (see Fig 3) had approximately the same area-volume relations as those

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measured for the cadaver used for this study it is clear that the geometric shape chosen is far from ideal for application to all mammalian species, including man. In fact, work is now under way employing a truncated cone as a geometric model, a much more realistic shape. Also the analytical details are being refined to allow the areas of the sides and the base of the cone to change as the simulated lung volume changes during the implosion process. Additional refinements may result from studies which are planned in which cross-sections similar to those described in Sec. 4.3 will be made for various experimental animals.

6.3 The Estimated Parameters for 1-kg Animals and Intraspecies Scaling

The fact that physiological data were presented indicating that mammalian species appeared to fall into two groups -- one for "large" and the other for "small" animals -- deserves considerable emphasis. This segregation of the animals of interest was reflected in the best estimates for model parameters presented in Table 1 wherein figures were given for "small" and "large" species all scaled to the 1-kg animal along with reference to the scaling equations allowing one to estimate the parameters for an animal of arbitrary size. Again it is necessary to emphasize that the numerical data given represent only approximations, but it is easy to appreciate the desirability and need for obtaining accurate numbers for all parameters along with a fair assessment of the normal variability associated with each. For example, one of the problem areas in blast and shock biology, that of estimating human tolerance to blast-induced pressure variation, would be better illuminated if the model parameters in Table 1 were known to be proper.

6.4 Review of Various Estimates of Man's Response to Overpressure

First, consider Fig. 10 showing the results obtained by Fisher, Krohn and Zuckerman[54] using mice, guinea pigs, rabbits, and monkeys exposed in wire cages and goats restrained in the standing position with rope netting, tail-on to the detonation of 1, 8, and 66 2/3 lb. PAG charges at ground level. Pulse durations were stated to range from 1 to 3 msec. Fig. 11, giving the empirically extrapolated relationship between the P_{50} pressure and body weight, depicts a predicted P_{50} of 392 psi for the 60- and 460 psi for the 80-kg animal. In addition the authors cited field-study results of 12 instances of human exposure to blast for which the associated maximum overpressures were estimated to have been from 170 to 600 psi. The only death reported was for a situation for which the maximum overpressure was estimated to be 450 psi. Most of the individuals who survived showed symptoms of blast injury. Of these, 10 exposures were judged to be between 170 and 450 psi and the remaining case between 500 and 600 psi. It would help had estimates been reported for the duration of the blast waves and for the weights and types of charges producing them.

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RELATION BETWEEN (BODY WT)²/³ AND 50% LETHAL
BLAST PRESSURE FOR MICE, GUINEA PIGS AND RABBITS.
THE STRAIGHT LINE IS THE CALCULATED LINE
OF CLOSEST FIT

(A)

$P_{50} = 23.7 + 0.240 W^{2/3}$

P_{50}, psi

[Body wt, gms] 2/3
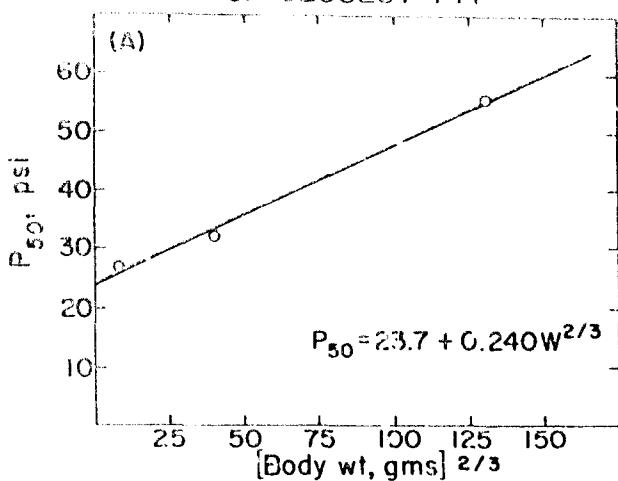
RELATION BETWEEN LETHAL EFFECT OF BLAST AND
BODY WEIGHT IN MONKEYS AND GOATS. THE DOTTED LINE
REPRESENTS THE EMPIRICAL RELATION SHOWN IN THE CHART ABOVE

(B)

Maximum Overpressure, psi

Goats

o   Survived
●   Killed

—Monkeys

Body wt, kg
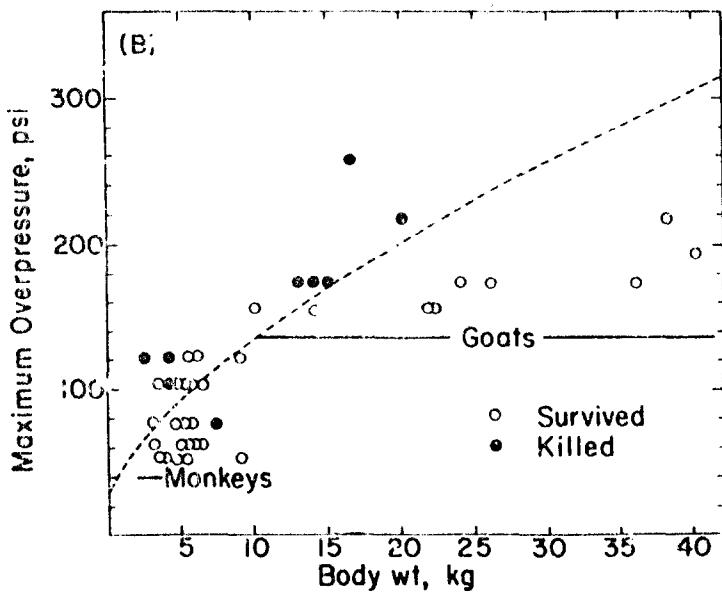
Fig. 10   Mortality data from studies by Fisher, Krohn,
and Zuckerman[54] in which animals were exposed tail-on
to the detonation of high explosive charges at ground level.

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EMPIRICAL RELATION BETWEEN P_50 AND BODY WEIGHT DERIVED BY EXTRAPOLATION FROM FIG. 10(A)
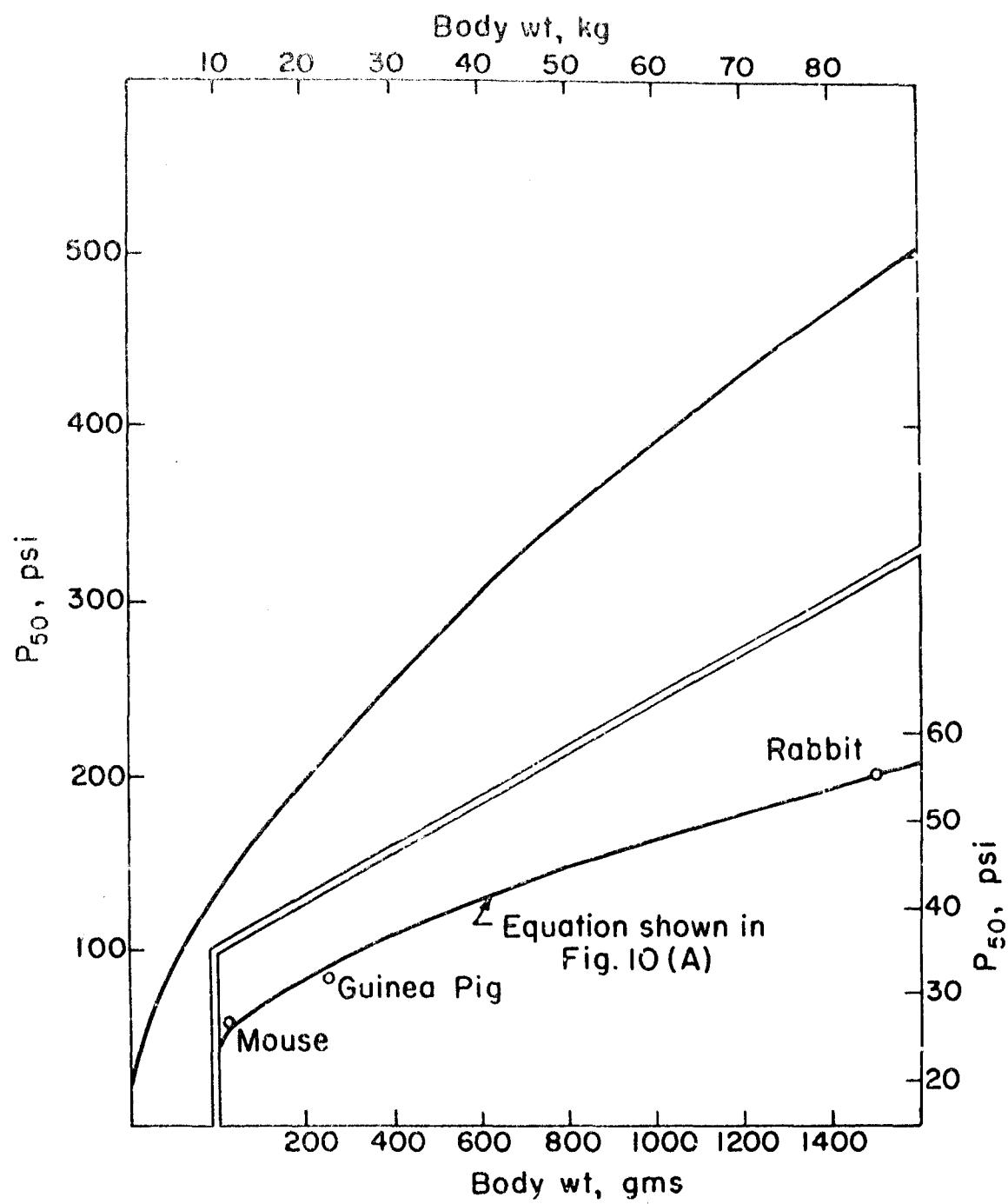
Fig. 11   Extrapolation of the data shown in Fig. 10 to
body weights up to 90kg.   Pulse durations ranged from
1 to 3 msec

Second, attention is directed to Fig. 12, a summary type illustration taken from the work of Schardin,[31] indicating on a weight-of-charge vs. distance diagram that tolerance curves for physical and biologic media have certain similarities; viz., the curves are nearly parallel with the isopressure lines for "larger" charges at the "greater" distances ("long"-duration waves) and approach parallelism with the isomomentum lines for the "smaller" charges at the "lesser" ranges ("short"-duration waves). The curve Schardin cited for dogs, drawn from the data of Desaga,[3] is replotted in Fig. 13 on a pressure-duration diagram to show just fatal conditions for dogs which were exposed on the ground in either recumbent or erect positions. Open cylinderical charges (height equal to the diameter) of FP 60/40 (60 percent ammonium nitrate, 40 percent hexogen) were placed and detonated on the ground. It is significant that a pressure of 215 - 220 psi was required for lethality when the pulse duration was 1.6 msec, but when the latter was 11.8 msec the just-fatal pressure was only 76 psi. The charge weights, lethal limits, pressure, and duration data for the Desaga experiments are tabulated in Table 2 shown below.

TABLE 2

EXPLOSIVE WEIGHTS, DISTANCES,

PRESSURES, AND DURATIONS ASSOCIATED

WITH LETHALITY IN DOGS

TABULATED FROM THE DATA OF DESAGA[3]

Explosive Weight kg	Lethal Limit Meters	Static Maximum Pressure psi	Pressure Duration msec
25	4.25	216	1.6
50	5.30	218	1.6
200	9.7	125	4.1
1000	19.0	85	8.6
1500	22.0	79	10.3
2000	25.0	76	11.8

That Table 2 and Fig. 13 demonstrate a decrease in the lethal overpressure by almost a factor of 3 (218/76 = 2.9) when the pulse duration is increased by more than a factor of 7 (11.8/1.6 = 7.4) deserves considerable emphasis. Not only do the data confirm the observations of Hooker[1] and Clemedsen[6] that both pressure and duration are important factors in blast tolerance for relatively "short" pulses, but they represent the first quantitative results defining the magnitude of the pressure-duration effect.

To note the relationship of human tolerance for "short" duration pulses to the animal work just cited, attention is directed to Fig. 14

41
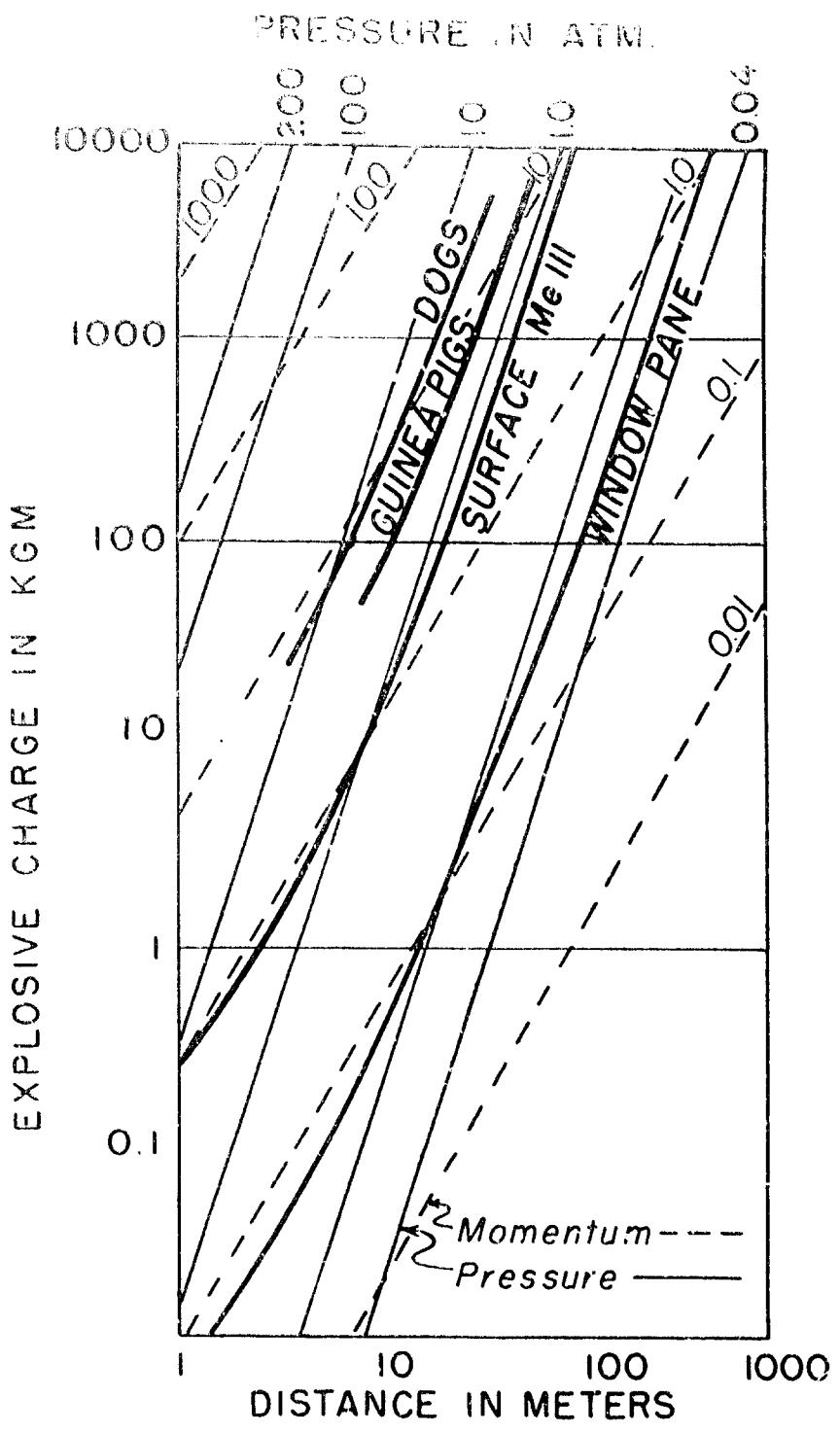
Fig. 12 A charge-distance diagram modified from Schardin[3] showing characteristic lines of destruction for animals and inanimate objects. (Momentum expressed in atm-msec)

42
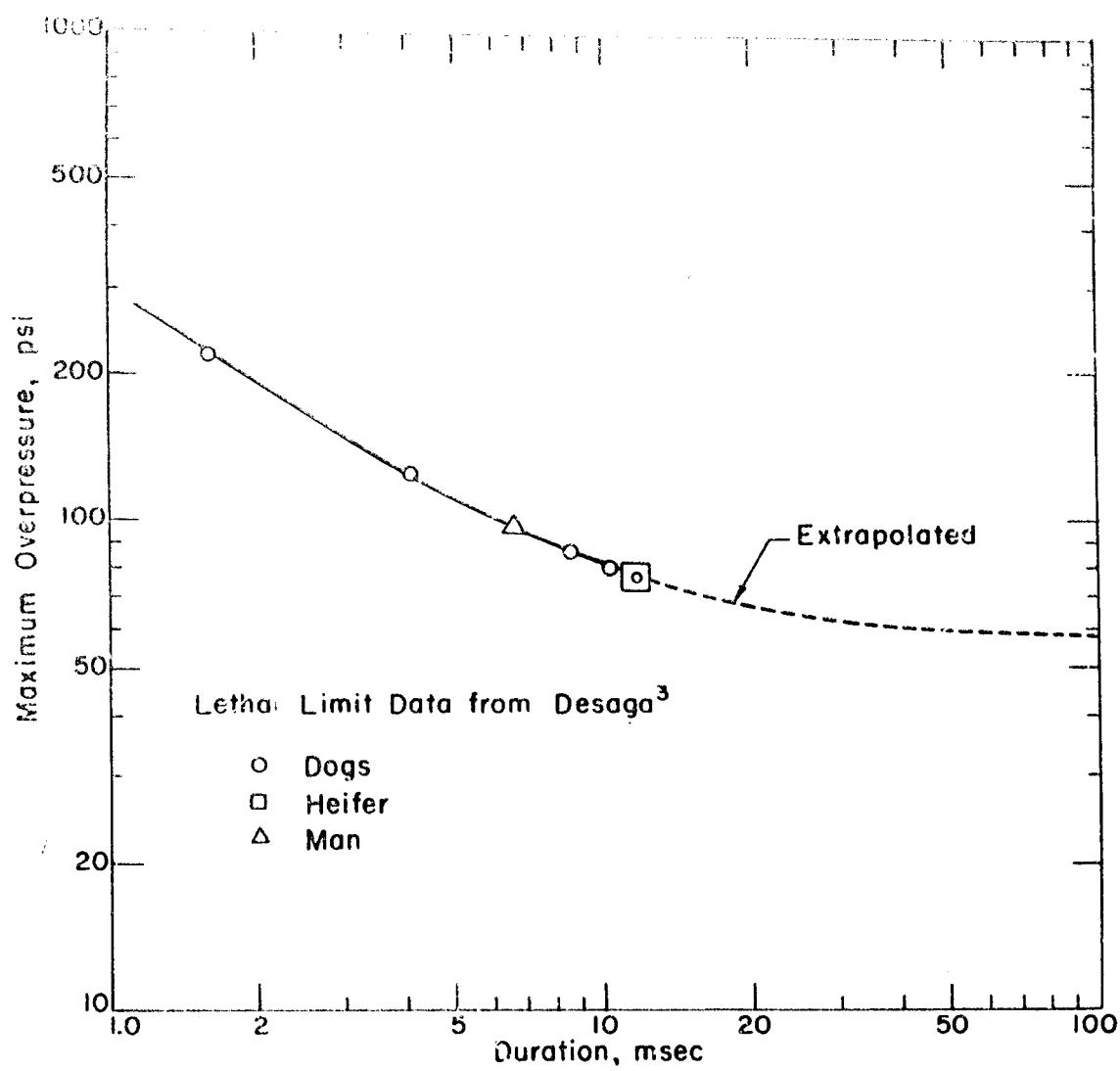
Fig. 13 Experimental data of Desaga[3] showing the "lethal
limit" for dog and heifer. The point indicated for man
(100 psi, 6.6 msec) was estimated by Desaga as a result
of an investigation of a bombing incident during the Second
World War. See text.
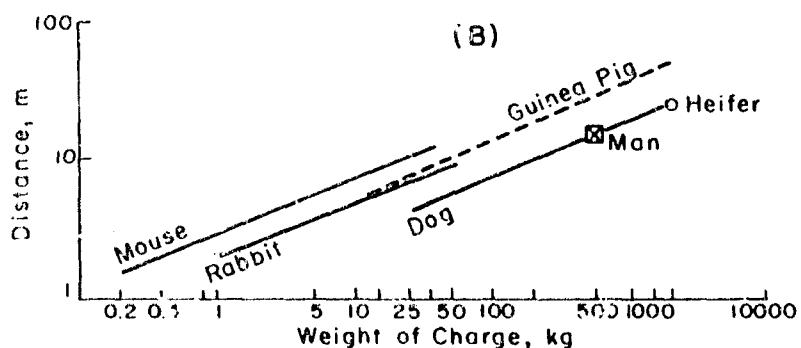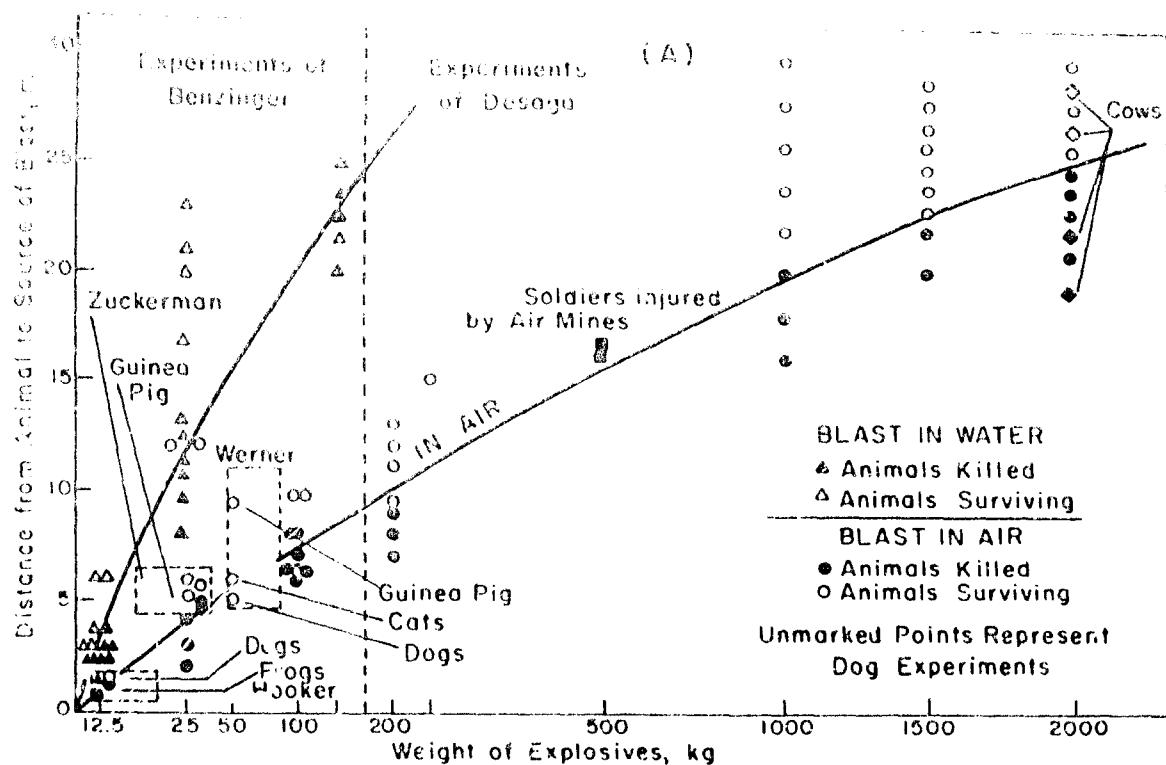
Fig. 14 (A)   Air-blast mortality data as summarized by Benzinger.

Fig. 14 (B)   Lethal limit data from studies by Desaga.[3]   Also see
Fig. 13.

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showing summarizing charts taken from Benzinger[4] and Desaga.[3] The latter shows a point labeled "man" to be on a line defining lethal limits for dogs and heifers on a weight-of-charge vs. distance diagram. The former indicates similar data that allows one to appreciate the relation of the human data point to the dog experiments cited in Table 2.

The human data referred to by both Benzinger[4] and Desaga[3] were presented in detail by the latter. Exposure of 8 individuals in an open-topped anti-aircraft gun emplacement occurred following the detonation of a 2,000 lb. HC bomb (total weight 918 kg, charge weight 550 kg). All except one of the exposed men were injured, two fatally. The fatal cases were located near a corner where pressure reflection occurred. Desaga estimated the incident overpressure to be 57 psi, with a reflection to a maximum of 235 psi. The duration of the pulse was not stated, but was likely to have been about 7 msec. Also, it is not possible now to say how much time might have elapsed between the occurrence of the incident and reflected spike at the location of the fatally injured men, but there might well have been a delay of more than 1 or 2 msec, a fact that could have increased tolerance significantly. Finally, one must point out that one of the fatally injured individuals also suffered a fractured skull, a fact that indicates decelerative impact as well as primary blast might have been a factor in lethality. Even so, the condition of the lungs described was typical of primary blast injury and no doubt the latter contributed mostly to death which occurred about 45 minutes after exposure for each case.

Making use of the human data described above, Desaga estimated that the "lethal limit" for man was 6,8 atmospheres overpressure (100 psi for an ambient pressure of 14.7 psi) for a charge of 550 kg. A duration of 6.6 msec was estimated for this situation by graphical interpolation of Desaga's blast data presented in Table 2.

Third, Richmond et al.,[10] using data obtained at Albuquerque (12 psi ambient pressure) partly shown in the pressure duration diagram in Fig. 15 for over 3,000 animals distributed among 6 mammalian species, extrapolated the findings using both "small" and "large" animals to predict 1, 50, and 99 percent lethal conditions for the 70 kg mammal as noted in Fig. 16. Animals were either exposed side-on against the end-plate of a shock tube or lying on the ground with charges detonated vertically above. In each case, the animal was exposed to the "fast"-rising incident pulse followed almost immediately by the reflected pressure.

The approach used by Richmond et al.[10] to extrapolate the animal data to the 70 kg mammal is illustrated in Fig. 17 for "fast"-rising, 400-msec waves. Note that this figure also includes data for the hamster and the cat[51] which became available after the original estimates were made. The additional data, however, did not significantly change the P_{50} estimate for the 70 kg mammal, 52 psi, which figure scaled to sea-level ambient pressure becomes 52 (14.7/12) psi = 64 psi. The latter is close to the 62 psi value noted in Fig. 9 of the present study, a number obtained

Overpressure For 50 Per Cent Lethality As A Function Of Duration
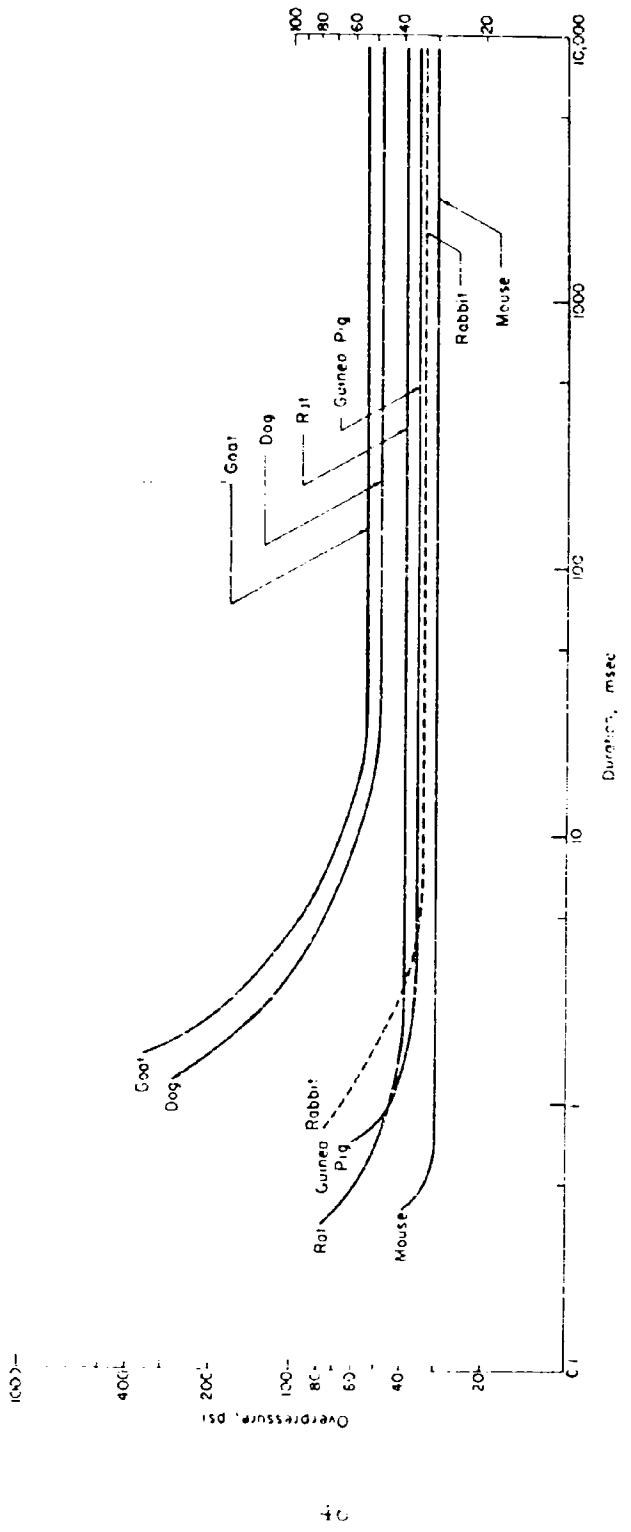
Fig. 15   Summary of the overpressure-duration relationships resulting in 50 percent mortality for animals exposed side-on against the end-plate of a shock tube or lying on the ground with charges detonated vertically above.   Data from Richmond et al.[10]

The Overpressure-Duration Relationship
calculated for 1, 50 and 99% lethality
for the 70Kg mammal.
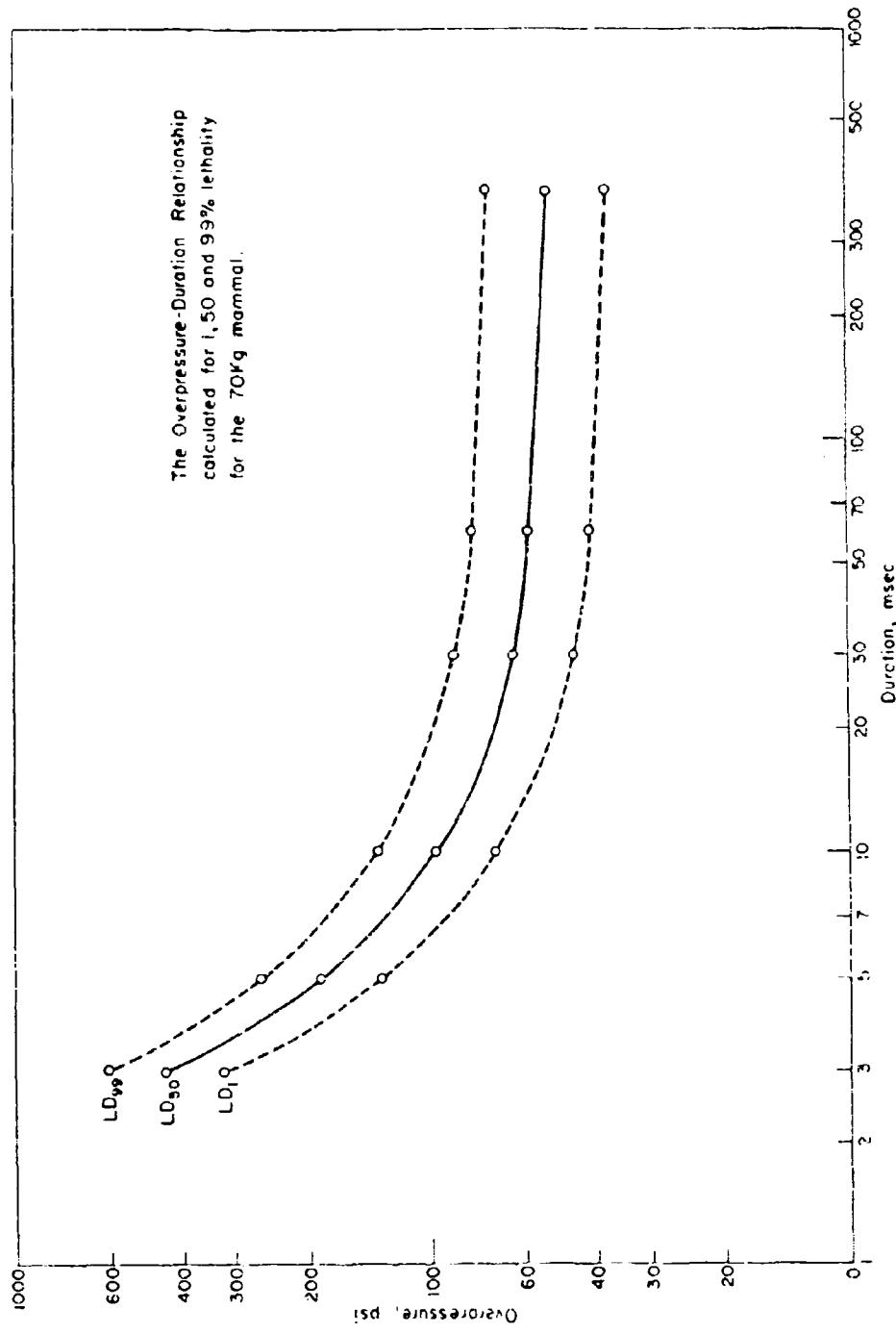
Fig. 16   Results of body-mass extrapolation[10] of the data shown in Fig. 15 to a 70-kg
mammal. Ambient pressure: 12 psi.

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P_{50} : Reflected Overpressure Producing 50% Mortality When The Animal Was Against The End-Plate Of The Shock Tube

Ambient Pressure : 12 psi

Mouse

Hamster

Rat

Avg : 48.1 psi Cat

Guinea Pig

Rabbit

Avg : 31.9 psi

Goat

Dog

70 kg
52.3 psi

Regression Equation: Log P_{50} = 1.5753 + 0.07755 log m

Body Mass (m), kg

P_{50} : psi

200

100

50

20

10

.01 .02 .05 .1 .2 .5 1.0 2.0 5.0 10 20 50 100
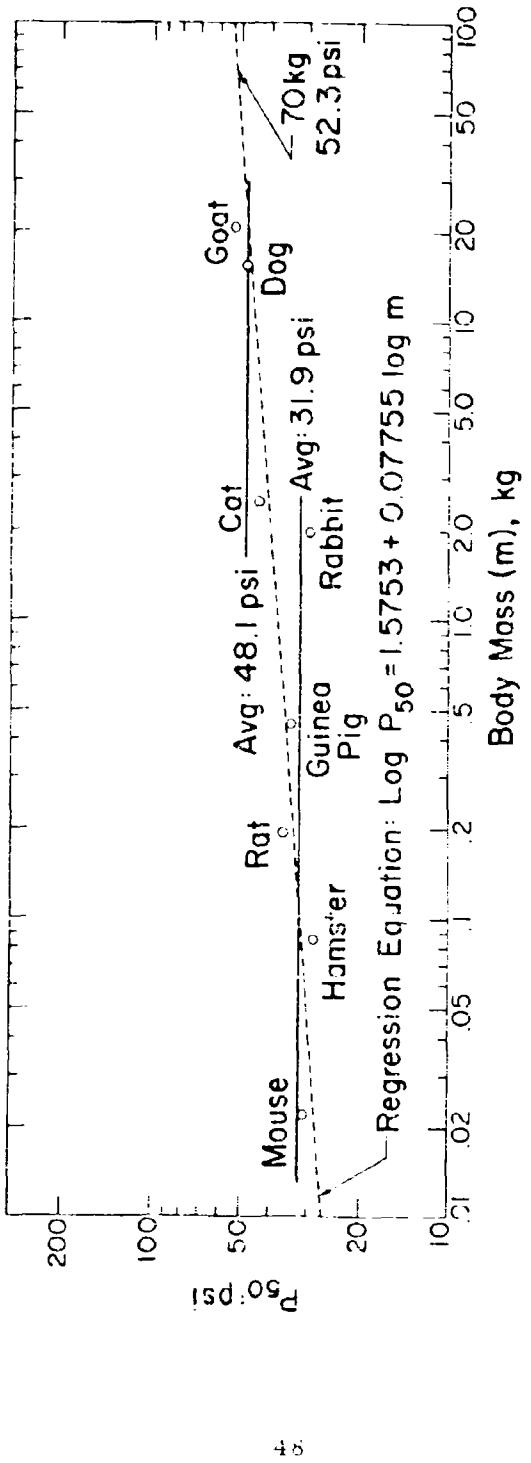
Fig. 17 Illustrating the method used in Ref. 19 to extrapolate P_{50} as a function of body mass using data for animals exposed to blast waves of a given duration (400 msec in this instance).

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employing the scaling equations and the empirical data of Richmond[10] for dogs and goats.

Two horizontal lines were drawn in Fig. 17, one through the "small"- and the other through the "large"-animal data, to raise the question as to whether or not the animals are actually divided into two distinct groups, one of which may include man (see Sec. 5.3). The alternate assumption is that all the experimental animals are members of the same group and that tolerance to 400-msec blast waves is a function of body mass as illustrated by the dashed regression line in Fig. 17. Although the scaling or extrapolation procedure used may not be too important for the "longer"-duration pulses, it is for the "shorter"-duration blast waves. Table 3 is included to compare the results of the scaling approach described in Sec. 5.5 using only the goat and dog data with the results of the extrapolation made by Richmond et al.[10] employing both "large"- and "small"-animal data. This table also includes the estimates of man's tolerance to air blast made by Fisher, Krohn, and Zuckerman[54] and Desaga.[3]

The information presented in Table 3 is shown graphically in Fig. 18. Since the animal work of Fisher et al.[54] applied to 1 to 3 msec pulses and their estimates were made for 60 to 80 kg animals, the extrapolated data are shown in Fig. 18 as a rectangle (dashed lines) whose sides were placed at the appropriate limits. It is apparent that the estimated tolerance curves of the present study would pass through this rectangle if they were extended to shorter durations. Desaga's estimate of the lethal limit for man, shown as a point in Fig. 18, is located -- perhaps fortuitously -- within about 2 psi of the estimated tolerance curve of the current study for 14.7 psi ambient pressure. For blast waves with durations greater than 100 msec which are particularly apropos of nuclear weapons, the extrapolated curves of Richmond et al.[10] and the scaled curves of the present investigation agree within 10 percent. For durations of 3 msec, however, the former P_{50} estimates are 2 - 3 times as large as those of the latter.

6.5 Other Applications of the Model

In addition to the use of the model described in the present study to help formulate human tolerance criteria from data obtained with various species of animals, other applications are of interest. For instance, the computation of intrathoracic pressure-time variations in various animals exposed in comparable blast environments not only helps one understand the contributions of critical body parts involved in the implosion process, but can also contribute to the study of the biophysical mechanism etiologically active in causing the highly hazardous blast injury to the lungs.

The model allows, for a given animal, a comparison of the effects of one blast situation with that of another and, for a given blast situation, a comparison of the response of one animal with that of another.

TABLE 3

A SUMMARY OF VARIOUS ESTIMATES OF MAN'S TOLERANCE TO AIR BLAST

Tabulated overpressures in psi correspond to 50 percent mortality except where noted. (P_0 : ambient pressure)

Duration, msec	$P_0 = 14.7$ psi				$P_0 = 12$ psi	
	Present Study	Ref. 10	Ref. 54	Ref. 3	Present Study	Ref. 10
1 - 3	≈ 340[*]	>1000[*]	392-469[**]		-	-
2	290	-			-	-
3	188	528			170	431
5	120	227			106	185
6. 6	98	166		100[***]	86	135
10	79	120			68	98
20	64	87			54	72
30	62	78			51	64
60	62	71			51	58
400	62	64			51	52

* Extrapolated to 1.73 msec.

** Lower and higher overpressures apply to 60- and 80-kg animal, respectively.

*** "Lethal limit" values of overpressure and duration.

50
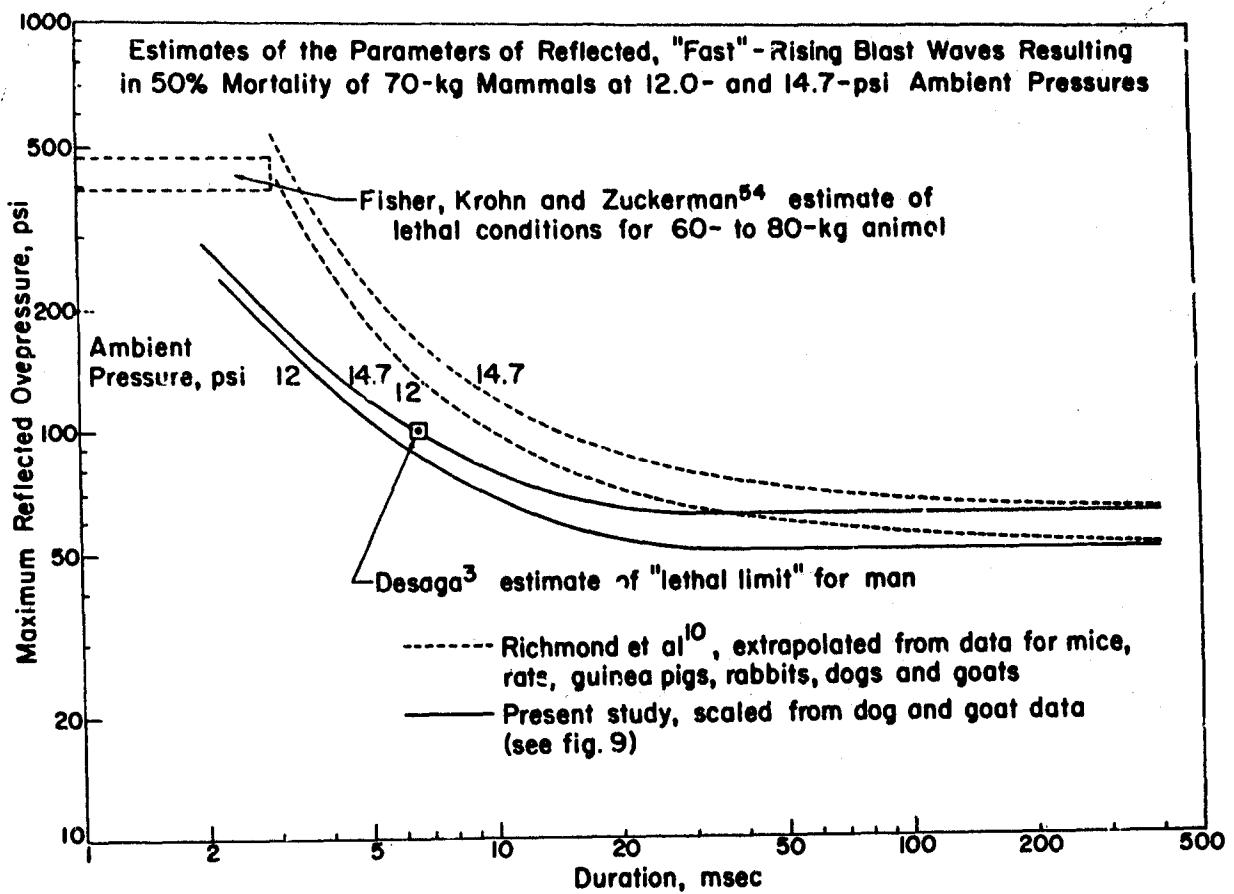
Fig. 18 A comparison of various estimates of man's tolerance to air blast. See Table 3.

The "lung" model, along with the scaling relations presented in this report, could be used in related studies such as the biological effects of explosive decompression, high noise fields (oscillating ambient pressures), and a whole variety of other disturbed or atypical blast-induced wave forms. In some of these areas, unlike the case for the very rapid changes in blast pressures associated with typical or near-typical wave forms, flow in the airways may be an important mechanism of compensation. It certainly can be in explosive decompression, and thus a more accurate air flow expression than the one reported here wou .d be desirable.

In closing the discussion, it is well to emphasize that the present study helped elucidate the very important part played by the non-linear air spring which is estimated, for small species exposed at sea-level ambient pressures, to be more than 500 times as "stiff" as the mechanical spring (K_1 and K_2) discussed in Sec. 4.4 and alluded to in Eq. (65) and in Table 1. This significant fact should not be lost sight of and it needs be explained that the air-spring effects enter the model equations somewhat indirectly through the pressure-volume relationship as discussed in connection with Eqs. (38) - (41). Thus, the response time of the thoracic-abdominal system to blast loading is a function of the magnitude of the pressure; i.e., the thoracic pressure will rise to a maximum earlier for a high than it will for a low overpressure. That high overpressures are necessary at higher ambient pressures to achieve the same biological response can be related to the fact that the air spring is stronger in the latter case. Also, the stiff air spring no doubt is a very important factor in the "adaptation" an animal makes to a non-lethal incident pulse which completely protects him against the associated and otherwise lethal reflected pulse provided the two increases in external pressure are separated enough in time to allow the intrathoracic pressure to rise significantly, or to a maximum, in response to the initial pulse. In such circumstances, the internal pressures are high and thus the animal is a "stiffer" system which can better resist the effect of the second pulse. This probably means that if the stiff air spring factor were not at work, the second component of a stepwise increase in air pressure would be significantly more effective than it is.

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7.0   SUMMARY

The highly lethal effects of exposure to "fast"-rising blast-induced overpressure, the extraordinary sensitivity of the mammal to small changes in the average rate of pressure rise, and the recent speculations covering the etiologic and "protective" significance of the internal pressure rise as a consequence of the violent implosion of the body wall by blast waves were cited as reasons for exploring the utility of a simplified model of the mammalian thoraco-abdominal system to guide thinking about the implosion process and its etiologic relations to air blast injury.

The mathematical model, conceived to simulate mammalian response, incorporated (a) the equations of motions of "chest-wall" and "abdominal" pistons allowed to move into a confined volume representing the gas contained in the lung and airways and (b) an expression describing gas flow through an orifice serving as a communication between the confined "lung" gas and that in the external environment.

The following parameters of the model were defined:

a. The average gaseous volume of the lungs.

b. The effective areas, masses, spring constants, and damping factors of the pistons representing the abdomen and the chest wall.

c. The effective area of the orifice representing the airways.

The assumptions made in formulating the model equations (which were integrated by numerical methods making use of a digital computer) were:

a. The pressure-volume changes in the cavity representing the lungs were polytropic with an exponent of 1.2.

b. Though the gas confined in abdominal organs obviously influenced the implosion process, the effect was insignificant.

c. The complex movement of gas to and from and within the airways of the lung could be adequately simulated with a simple orifice with an appropriately chosen coefficient.

d. The temperature and pressure of the gas in the lungs were uniform over the entire volume at any given instant.

Scaling equations were developed for the animal parameters based on the principle of (a) similarity of shape and (b) equivalence of the tissue-mass and tissue-elasticity distributions. By dimensional analysis,

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the relation between body mass of similar animals and blast-wave parameters were formulated for the condition of equal biological response, as indicated by any nondimensional index, such as percent mortality.

The parameters of the model were evaluated through a variety of approaches, some of which are noted below.

a. Evidence cited from the literature indicated that the ratio of the average lung volume to average body mass was about 9 cm^3/kg for "smaller" animals (mice, rats, guinea pigs, and rabbits), but was significantly higher, near 30 cm^3/kg, for "larger" animals (monkeys, cats, dogs, man).

b. The average lung densities for the "smaller" species were reported to be higher than for the "larger" animals, 0.367 compared with 0.194 g/cm^3.

c. A geometric model of the thorax was devised using cross-sections of a human cadaver reported in the literature. Assuming similarity of shape, scaling equations were developed relating areas and masses of the chest-wall and abdominal pistons to lung volume and density.

d. Published velocity resonant frequency data for cats and dogs were used to estimate the total spring constant, which was apportioned to each of the pistons on the basis of mass.

e. The effective orifice area was scaled from data reported for rapid decompression studies in man.

f. The damping factor was estimated by analyzing two records of intrathoracic pressure for 1.8-kg rabbits exposed to blast waves generated by shock tubes.

All the animal parameters were tested against the experimental records mentioned above (f) by solving the model equations for the measured shock-tube waves using parameters scaled to a 1.8-kg rabbit. Adjustments were made in most of the parameters in order to achieve better agreement between the computed and measured thoracic pressures. Graphical comparisons were made between the experimental and computed pressure records and the adjusted parameters were listed along with those estimated.

Certain selected applications of the model and scaling equations to problems in blast and shock biology were worked out. Among them, along with other matters of interest, were the following:

a. Application of the scaling equations indicated that the mortality of similar animals would be the same, regardless of body mass, when exposed under similar conditions to a

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"long"-duration shock wave that does not decay appreciably during the short time necessary for the lung pressures to reach the peak values. A test of this theory, using published data, indicated that the mouse, hamster, rat, guinea pig, and rabbit are approximately similar, but that the cat, dog, and goat have a significantly higher blast tolerance.

c. Published data were used to show (according to the scaling equations for similar animals) that the mouse, rat, guinea pig, and rabbit have approximately equal sensitivity to time delays between the incident and the reflected shock waves if the times are made proportional to the cube root of the body mass. The time-step effect was also investigated by solving the model, with parameters for a 1.7-kg rabbit, for blast waves of increasing time steps similar to those measured in the shock tube. It was found that internal pressure resulting from the incident wave tended to inhibit the effects of the reflected wave.

d. By scaling procedures, estimates were made of the parameters of reflected, "fast"-rising, blast waves which would result in 50 percent mortality for 70-kg mammals when exposed at 14.7-psi ambient pressure. The published data used to make these estimates were results of shock-tube and high-explosive studies at 12-psi ambient pressure with 22.2-kg goats and 16.5-kg dogs exposed against reflecting surfaces.

In discussing the results, mention was made of the fact that information currently available does not allow the responses of the abdomen to be distinguished from those of the chest wall. Work likely to be appropriate and relevant to improvement of the geometric model of the thorax (a truncated cone rather than a cylinder) was noted and the tentative and approximate nature of the model parameters evaluated for the idealized 1-kg "small" and "large" animal was emphasized.

Three approaches to assessing man's response to overpressure were reviewed and compared with that presented in the present study. Two of the estimates for tolerance to short-duration waves were shown to be consistent with those presented herein. The third approach resulted in estimated human tolerances which were approximately the same as those proposed in this report for blast waves of "long" duration but were significantly different for pulses of "short" duration.

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13. ABSTRACT

A mathematical model was described which was developed to compute some of the fluid-mechanical responses of the thoraco-abdominal system subjected to rapid changes in environmental pressure. The approach -- helpful in understanding many of the primary effects of air blast on animals, but applicable to related problems involving rapid changes in environmental pressure as well -- incorporated an air cavity representing the gaseous volume of the lungs (although it is recognized that gas in the organs of the abdomen may influence the response of the system), two movable pistons and an orifice through which gas might pass in either direction. One of the pistons represented the chest wall and the other that portion of the abdomen which moves with the diaphragm to change the lung volume. Each piston was "assigned" an effective mass and area, a spring constant, and a damping factor. The orifice was taken to "incorporate" the characteristics of the many airways of the respiratory system. Parameters relating the animal to the model were estimated, tested and then adjusted as required by comparing model results with experimental records of thoracic pressures recorded for rabbits exposed to blast waves in shock tubes.

Equations were derived to scale parameters applicable to a given animal to those for similar creatures of arbitrary mass. By dimensional analysis other equations were developed to relate, for a given biological response, the body mass of similar animals to blast wave parameters. Numerical solutions of the model were

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presented to help explain the mechanisms involved when animals were "loaded"
with typical wave forms or with pulses increasing to a maximum in a stepwise
manner, a contingency associated with a quite significant increase in mammalian
tolerance to over-pressure. Differences in response to "short-" and "long"-
duration blast waves were noted. Applications of the scaling concepts were
exemplified in several ways making use of the published data in blast biology.
In one instance, the blast tolerance of a 70-kg mammal was estimated for sea-
level ambient pressure making use of experimental data for dogs and goats
obtained at Albuquerque altitude (ambient pressure of 12 psi). That the latter
might have significant implications in assessing human response to blast-pro-
duced overpressures was discussed along with several other relevant matters.